■ *IES Report 130*

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Part 1: Hydrologic Impacts

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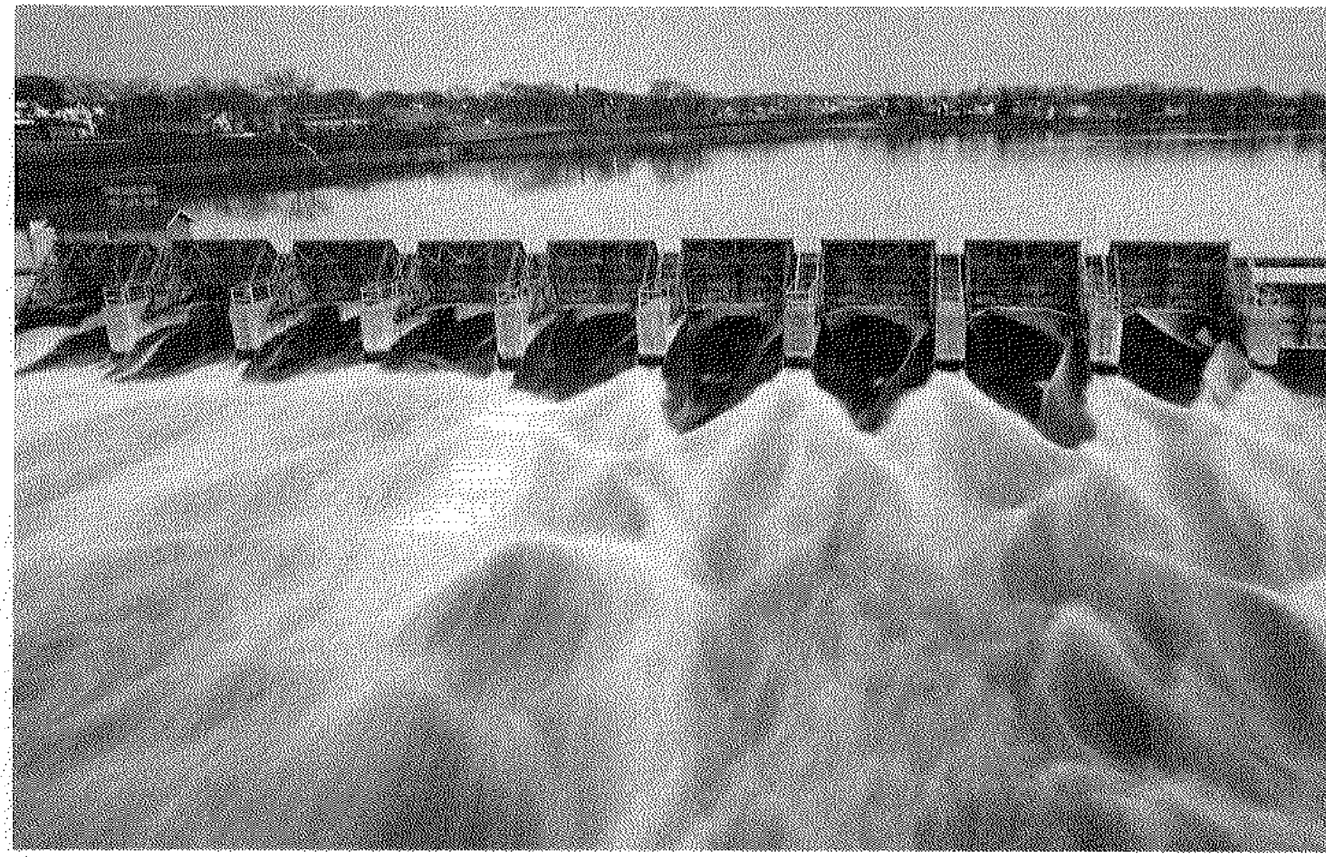

IES *Institute for Environmental Studies* ■ *in cooperation with the University of Wisconsin Sea Grant Institute*

University of Wisconsin-Madison

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ABSTRACT

This report describes the findings of the Great Lakes water management study at the University of Wisconsin-Madison. The study had the objective of developing a sound strategy for evaluating impacts caused by major water diversions if one were actually constructed. The evaluation strategy has two main components: hydrologic assessment and economic assessment. This report deals with the former while the economic component is addressed in a second report by the same authors.

This report provides a detailed description of the recommended strategy for determining the hydrologic effects of diversions. These effects are expressed in terms of the amounts by which water levels and flows decrease. Both short-term and long-term impacts may be deduced.

In chapter 1, highlights of previous research with parallel objectives are presented to introduce the reader to the wealth of Great Lakes water level information. The next two chapters deal with the hydrologic database and the Great Lakes hydrologic response model, which is used to simulate water levels from historical records of water supply and any selected management policy. The fourth chapter is devoted to two topics. First, there is presentation of the specific modifications to the hydrologic response model introduced by the Wisconsin study group. Second, the procedure given is used for development of diversion scenarios. Results and key conclusions of the study are given in the last chapter.

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The original version of the Great Lakes hydrologic response model was provided by the Detroit office of the U.S. Army Corps of Engineers.

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INTRODUCTION

This paper, "Diversion of Great Lakes Water, Part 1: Hydrologic Impacts," and the companion paper entitled "Diversion of Great Lakes Water, Part 2: Economic Impacts," describe the findings of the Great Lakes Water Management Study performed at the University of Wisconsin-Madison under the direction of the University of Wisconsin Sea Grant Institute. The objective of the multiyear study was to identify appropriate methodologies for assessing diversion impacts. In this context a diversion is a transfer of water through a pipeline or open channel from one watershed to another. This report describes a hydrologic model that illustrates changes in water levels caused by diversions. The companion report translates these changes into economic consequences.

Several diversion proposals have been discussed in recent years. Among these were proposed coal-slurry pipelines that would carry coal and water in a 50% mixture from mining areas in the West to users in the Midwest. The water for such systems would have to originate in the Midwest because none is available in the western coal fields. Also, the U.S. Army Corps of Engineers was studying the possibility of diverting additional water from Lake Michigan into the Mississippi River watershed and had, in fact, requested permission to test the existing diversion at higher flows. A backdrop to these comparatively minor proposals is the 20-year-old proposal to create the North American Water and Power Alliance (NAWAPA), an idea that receives recurring attention. The NAWAPA project basically calls for cross-connecting every watershed on the continent, largely to allow regions undergoing dry periods or experiencing growing water demands to share water with areas receiving sufficient rainfall. NAWAPA also envisions a number of diversions both into and out of the Great Lakes. Although the entire scheme will probably never be realized, subprojects have been built. One such subproject is the Garrison Diversion from the Missouri River watershed into the watershed of the Souris River.

The purpose of the study described herein was to create tools and methodologies to analyze potential diversions. Complete evaluation of such proposals entails analysis of both project costs and anticipated benefits. This study analyzed only the hydrologic impacts on the Great Lakes system in assessing the costs associated with changes in the lakes' water level regimes that result from diversion. For information on construction and operating costs of specific diversion projects that have been proposed, the reader is referred to Banks (1982); DeCooke, Bulkley, and Wright (1984); and the Proceedings of the Ontario Water Resources Conference (1984).

Initially, this project focused on the history of Great Lakes water level regulation. In particular, attention was given to computer modeling strategies that have been used to evaluate various regulation policies. Subsequently, these modeling strategies were adapted for evaluating Great Lakes water diversions. Finally, the modified computer models were used to evaluate several hypothetical diversion scenarios.

CHAPTER 1

BACKGROUND

North American Great Lakes Basin

Throughout the world are lakes that, through sheer area and volume, are recognized as great lakes. They possess special features that set them apart from lakes of more pedestrian dimensions. Perhaps 40 water bodies on the planet deserve the classification. But the North American Great Lakes hold a unique place among the world's large lakes: The five distinct basins of Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario combine to form a single watershed with one common outlet to the ocean. Nowhere else is there a similar collection of great lakes.

The enormous volume of water held in each of these lakes was originally supplied by the melting of the retreating Wisconsin stage glacier. It filled the deep gorges left by the ice movement of that glacial event and three earlier glaciations in the Cenozoic era. Hence, the same process that supplied most of our vast stores of groundwater was also responsible for filling the Great Lakes (GLBC 1975-76, p. 25). The total volume of the lakes is about 5,475 cubic miles, more than 6,000 trillion gallons. This volume could provide 50 gallons per day to each human being on the planet for an entire 75-year lifespan. But such computations are deceptive. Like many groundwater supplies, the Great Lakes are in large part nonrenewable sources of water. Only a fraction of each lake participates in the dynamic phase of the hydrologic cycle in which water courses through the environment. In other words, the natural range in variation between the least and greatest lake volume experienced in our climatic regime is a small percentage of the lake's total volume. For the basin as a whole, this range is just 75 cubic miles, or 1.4% (GLBC 1975-76, Appendix 11, pp. 7-8).

The Great Lakes are located along the 45th parallel. The direction of flow follows a sinuous path toward the east. Lake Superior is located at the highest elevation above the sea (about 600 feet) and farthest to the west. It drains into Lake Huron via the St. Marys River. Lake Michigan also empties into Lake Huron; it is possible, however, for flow between these two lakes to reverse. Because of the large connecting channel, the Straits of Mackinac, these two lakes equalize rapidly whenever a water level imbalance occurs. Gage records for the lakes clearly show them to have identical water level regimes and mean long-term behavior; that is, Lake Michigan and Lake Huron act as one lake for many purposes. In such situations, they are referred to in the singular as Lake Michigan-Huron.

Lake Huron outflow reaches Lake Erie by flowing from north to south through the St. Clair River, Lake St. Clair, and the Detroit River. Lake Erie drains through the Niagara River, which flows almost due north. The most downstream lake in the system, Lake Ontario, is 325 feet lower than the upper lakes. Only 30 to 35 feet of elevation are lost in traveling from Lake Superior to the Lake Erie discharge at the Niagara River. Lake Ontario outflow follows the St. Lawrence River for the remaining 500 miles to the Atlantic Ocean.

Usually, the basin is assumed to terminate at the confluence of the Ottawa and St. Lawrence rivers near Montreal. Downstream, the watershed lies entirely within Canada. Various physical data describing the Great Lakes are presented in tables 1, 2, and 3.

TABLE 1. Great Lakes water level data (in feet)

	Lake Superior	Lake Michigan-Huron	Lake Erie	Lake Ontario
Long-term mean				
(1860-1976)	600.37	578.70	570.36	244.77
(1900-1976)	600.52	578.20	570.13	244.62
Low-water datum	600.00	576.80	568.60	242.80
100-year high	602.06	581.94	572.76	248.06
100-year low	598.23	575.35	567.49	241.45
Recorded range	3.9	6.6	5.3	6.6
Estimated natural range	4.1	5.6	4.9	5.9
Mean summer high	600.83 (Sept)	579.20 (July)	571.04 (June)	245.61 (June)
Mean winter low	599.81 (Mar)	578.22 (Feb)	569.79 (Feb)	244.12 (Jan)

SOURCES: Great Lakes Basin Commission 1975
International Lake Erie Regulation Study Board 1981

TABLE 2. Areas of Great Lakes and their basins

Lake	Area Ratio	Lake Surface mi^2	Lake Surface km^2	Watershed Area mi^2	Watershed Area km^2
Superior	2.56	31,700	82,600	81,000	210,000
Michigan-Huron	3.15	45,360	117,500	142,700	370,000
St. Clair	15.20	430	1,172	6,520	16,900
Erie	3.38	9,910	25,680	33,500	86,840
Ontario	4.37	7,340	19,800	32,100	83,200
BASIN	3.12	94,680	247,000	295,800	766,900

SOURCE: Great Lakes Basin Commission 1975

Note: Area ratio is the ratio of the area of the basin to the area of the lake.

TABLE 3. Surface area/volume/depth relationships for lakes and watersheds in the Great Lakes Basin

Lake	Lake Areas		Basin Areas		
	tcfs months per foot	tcfs months per cm	tcfs months per inch	tcfs months per cm	cms months per cm
Superior	337.8	11.00	71.40	28.10	314
Michigan-Huron	480.8	15.72	125.80	49.53	447
St. Clair	4.6	0.15	5.75	2.26	4.46
Erie	105.2	3.45	29.60	11.65	97.6
Ontario	80.0	2.62	28.30	11.14	75.3
BASIN	1,001.6	32.90	261.00	102.80	938

SOURCE: International Great Lakes Levels Board 1973

Notes: cms = cubic meters per second
tcfs = thousands of cubic feet per second

The average annual runoff for the Great Lakes basin may be determined from the average St. Lawrence River discharge of 251,000 cubic feet per second (cfs). Over a year, this is enough water to drain a bit more than three feet from the surface of the lakes and reduce their volumes by approximately 1%. Rain and snow, however, replenish the water at a similar annual rate.

Like a forbidding mountain range, the Great Lakes form a natural boundary dividing the United States and Canada. The lakes also provide a navigable waterway of great historical significance. They link supplies of iron ore and fossil fuels in the western reaches of the basin to manufacturing centers and export terminals in the central and eastern parts of the region. In recent decades, though, society has become less dependent on waterborne transportation, and local mineral resources have been substantially depleted. Meanwhile, ports such as Kingston, Ontario, and Green Bay, Wisconsin, once formidable military installations, have lost strategic importance. Consequently, they must rely on new activities for their vitality.

The Great Lakes are vitally important to the 36 million U.S. and Canadian citizens who live in the basin. An estimated 26 million of these inhabitants depend on the lakes for their domestic water supply (Council of Great Lakes Governors 1985, p. 6). Many are employed by industries that depend on water from the Great Lakes, including the tourism and recreation industry that flourishes in the basin. With an estimated value of $8 billion per year, recreation and tourism have shown solid growth in the region during the last 10 years (Council of Great Lakes Governors, p. 6). They are a bright spot against an otherwise bleak economic backdrop that has plagued the Midwest since 1970.

Great Lakes Water Level Variation

The water surface elevation of any one of the Great Lakes at any particular time and location is the result of many factors. Water level variations on these lakes exhibit widely ranging durations, rates of change, and magnitudes. Frequency analysis is an appropriate means of classifying such variations. This technique allows identification of the periodicity of various water level variations. For example, water waves have periods ranging from one to 10 seconds, during which the water level may drop and rise as much as 12 feet. A rocking motion known as seiching may occur in harbors and bays, causing variations of one or two feet in a steady cycle that repeats every 15 to 60 minutes. Each individual lake also has a seiching action affecting the entire shoreline. The driving force of seiches is the temporary local raising of water level by wind setup. Setup occurs when powerful storms induce water to flow to the downwind portion of the lake.

Wind setup is a major cause of Lake Erie shoreland flooding because the lake's geometry and orientation are favorable to large setups (Janney 1974, pp. 7-10). Rises of five feet persisting up to 48 hours are common at the eastern end of Lake Erie. Unusual weather conditions can lead to devastating floods along the shores of the Great Lakes. A storm with northeast winds prevailing will cause setup to occur at the west end of Lake Erie. High water in this part of the lake will tend to block flow from entering Lake Erie through the Detroit River, which in turn will raise the level of Lake St. Clair at an alarming rate. Typically, Lake Erie need only rise three or four feet (at the Toledo end) before water will be induced to flow back up the Detroit River into Lake St. Clair. A similar combination of unusual weather and bathymetry has been known to cause sudden rises of up to six feet in the area near Alpena, Michigan. An unexplained three-foot drop recorded at Milwaukee in 1921 may have been caused by unusual variations in atmospheric pressure in concert with other processes (Freeman 1925, p. 187).

The water level variations described are economically significant but have little relationship to Great Lakes management policy. Such variations are highly localized and are only tangentially related to the quantity of water in the lakes when an event occurs. The issues addressed in this report involve water level variations with mean periodic intervals greater than one year. Variations of this nature are caused by the process of basin supply, which arises from the random occurrence of streamflow, precipitation, evaporation, outflow, and perhaps groundwater flow. Human intervention manifested in outflow regulation, consumption, and water diversion also plays an important role in the observed year-to-year variations of Great Lakes water levels.

Each lake has an annual water level cycle. The level rises each spring in response to increased river flows. The rise continues through midsummer because precipitation exceeds evaporation. As the lake warms, evaporation increases and surpasses precipitation. By September, the annual peak has been reached and the lake level retreats towards its winter low. Heat storage in the lakes fuels evaporation well into the winter, while much of the potential supply remains on land as snow. The magnitude of the water level change experienced in the annual cycle increases with decreasing surface area of the lake. Average values range from 1.1 feet on Lake Superior to 1.8 feet on Lake Ontario. This annual cycle is rather regular and is thus of little economic significance because human activity on the lakes accommodates the associated water level changes.

Lake level variations of substantial importance occur over periods of several years when climatic variability leads to persistent water levels that are either above or below normal. The extremes in highs and lows show the overall range in water levels to be four to five times greater than the typical annual range. Some investigators believe that variations of this type follow a cycle lasting 20 to 30 years (Quinn 1981, p. 1622).

These long-term variations have been viewed as having great economic and political consequences because of their impacts on three important areas of economic activity directly related to the Great Lakes: (1) municipal and industrial water supply, (2) commercial navigation, and (3) hydroelectric power production.

At the beginning of this century, hydropower was nonexistent and navigation was severely limited by impassable rapids on both the St. Marys and St. Lawrence rivers and by the chronic shallows along the Detroit and St. Clair rivers. With the exception of the withdrawal at Chicago, domestic water supply using Great Lakes water, albeit prevalent, was insignificant in terms of consumption. The urban population of the basin was one-eighth of today's, and, similarly, industrialization of the upper Midwest was in its infancy and therefore of no consequence in terms of water demands.

The situation changed rapidly in the first decade of the century. Water resource development issues soon gained enough importance to warrant the renegotiation of the 1899 Boundary Waters Treaty between the United States and Canada (actually, the United Kingdom). A new Boundary Waters Treaty was ratified in 1909. In it, the two countries agreed to share international waters equally and to cooperate in their water-related development and protection. Although the treaty applied to all international waters along the 3,300-mile-long border (now 5,500 miles long) between the two countries, there is little doubt it was designed for management of the Great Lakes and that Great Lakes management issues led to its creation (Day 1972, p. 1121).

The issue of the day was hydropower. Private companies in each country were interested in tapping the hydroelectric power potential of the St. Marys River connecting Lake Superior with Lake Huron. In conjunction with and secondary to the power objective, the companies desired to regulate Lake Superior and open the river to navigation as well, thus gaining the right to levy tolls on those who passed through. The intent of the treaty was clearly to prevent either of the countries from monopolizing the available flow at a given location simply by building the first or the largest intake structure. Also, the parties wished to avoid international negotiations each time a new proposal involving the boundary waters was put forth.

The primary product of the 1909 agreement was the creation of a binational arbitration board called the International Joint Commission (IJC). The IJC consists of three representatives from each country who are appointed by the respective heads of state. The commission's function is to undertake the necessary research and make recommendations to the heads of state concerning proposed development of, and disputes involving, international waters.

The IJC has little real authority. Its recommendations are nonbinding, and it is prohibited from taking up issues on its own. Rather, the IJC acts only at the request of either government and is an advisory body that possesses limited surveillance and research functions. Another weakness is that the treaty does not sanction IJC control over Lake Michigan. Over the years, however, Lake Michigan has been included under IJC authority as the United States government sees fit.

The IJC does have an important role in the management of long-term variations of Great Lakes water levels. This role stems from the water use priorities set forth in the treaty. The priorities were given in the following order: (1) domestic water supply and sanitation, (2) navigation, and (3) power generation and irrigation. The equal ranking given to the latter two uses is puzzling as is the omission of fisheries and industrial water supply.

The conflicting priorities have caused the commission's primary function to b the investigation of long-term water level variations. This has proved necessary in order for the IJC to perform what has evolved into its major activity: setting criteria for developing regulatory policies that govern outflows from the controlled lakes. The 1972 and 1978 Water Quality Agreements between the United States and Canada diverted some of the emphasis away from water levels by providing additional responsibilities to the IJC; however, the historical mission remains evident (Donohue 1984). To avoid duplication, the actual IJC research activities are farmed out to qualified agencies of the federal governments on either side of the border; the commission itself establishes constraints and working criteria for policy development. During the past 20 years, the IJC has been requested to coordinate major studies of Great Lakes water level variations and their impact on society. These studies and their results are summarized in the following section. Citations for the multivolume reports generated by the projects are given in appendix 1.

Major Studies of Great Lakes Water Levels Performed under the Direction of the International Joint Commission

In October 1964, the IJC created the International Great Lakes Levels Board (IGLLB) to carry out a comprehensive study of variation and regulation of the Great Lakes water levels. The IGLLB consisted of experts from government agencies in the United States and Canada. There were between 12 and 15 full-time members, most of whom were employees of either the U.S. Army Corps of Engineers or Environment Canada. Numerous aspects of the IGLLB research effort were pioneering, if not unique, among all Great Lakes water levels studies. The IGLLB's approaches and findings continue to be relevant even though the study commenced more than 20 years ago.

A unique feature of the study, relative to earlier efforts, is the application of the digital computer. For the first time it became economically feasible to perform quantitative analyses of hydrologic processes as well as impacts on (and due to) human activity. Some of the software and certainly the methodology developed by the IGLLB are still in use today. In addition, portions of the final recommendations of the IGLLB study were eventually translated into regulatory policy. The study is also significant in its duration: Nearly a decade passed from the study's inception until the final report and nine volumes of appendices were published. Despite its bulk, the report did not document all of the work undertaken, and certain tasks involving state-of-the-art techniques relied on corroboration from academic institutions not connected with either government.

The primary objective of the IGLLB study was to " . . . determine whether measures can be taken in the public interest to regulate further the Great Lakes levels . . . so as to reduce the extremes of stage which have been experienced . . ." (IGLLB 1974, p. 4). The IJC order from which this is excerpted goes on to provide a list of secondary objectives in order of priority. The extreme stages mentioned are the record lows that occurred on Lake Michigan-Huron and Erie during 1963 and 1964, while the area was still feeling the effects of low levels experienced in 1959. Lake Superior, on the other hand, recorded no unusual deviations from its normal range of levels in any of these years. The words "regulate further" meant that the chief consideration to be addressed in this study was whether the construction of control works at the outlet of one of the yet-unregulated lakes would be economically beneficial. The phrase "in the public interest" implied that there should be minimal negative impact to certain Great Lakes economic activities. This is where the priority list of secondary objectives comes in. The text of the order called for an effort towards improving water level regimes, so benefits would accrue to the following activities in the following order:

-- domestic water supply and sanitation
-- navigation
-- water for power and industry
-- flood control
-- agriculture
-- fish and wildlife
-- recreation
-- other beneficial public purposes.

Most of these objectives demand the same regime of lake levels needed to satisfy the primary objective. There are two exceptions: flood control and navigation. Commercial navigation derives benefit from high lake levels, and there is no lower limit to the lake levels that are beneficial with respect to flood control. Assuming that the annual supply has a constant mean value, high lake levels do not provide any measurable benefit to hydroelectric power production because the plants are designed to operate under a head (elevation difference) that is nearly constant. Therefore the above list of objectives provides very few specific reasons to modify the existing lake level regime. One might conclude that the true objective of the IGLLB study was to investigate human disturbances of, and impacts on, the Great Lakes. The policy that resulted clearly protects existing uses and allocations regardless of their social value.

The IGLLB study was performed in four overlapping phases: (1) information gathering and model building, (2) development of alternative policies, (3) hydrologic evaluation, and (4) economic evaluation of the prospective policies. The hydrologic database and the associated modeling strategy developed for the first and third phases of the study are the basic tools used by regulation studies that followed the IGLLB study. Economic assessment has also played a role in the more recent work, although the techniques and the parameter values have been adjusted as needed. During the second phase of the IGLLB study, a dynamic programming optimization model was used to allocate monthly water supplies among the lakes. This step is absent in the later regulation studies.

Two studies that were similar in scope and methodology to the IGLLB study were performed by the International Lake Erie Regulation (ILER) Study Board and the Diversion and Consumptive Use (DCU) Study Board. Both study boards were created by the IJC to investigate means for improving water level regimes, subject to the preservation or improvement of various public interests in a manner similar to the IGLLB study.

The ILER study was completed in 1981. It focused on the problems of Lake Erie, which because of its shallow depth and small surface area is prone to frequent floods as well as recurrent shoals at harbor entrances, which impede navigation. The mission of the DCU Study Board was to determine the status of consumptive use in the Great Lakes Basin and to ascertain whether diversions of water into or out of the basin could be regulated so that water level regimes would be "improved."

The final report of the DCU study was released in 1981. This study has been heavily criticized for failing to address adequately some important issues. Part of its shortcoming may be traced to IJC restrictions upon the particular diversions to be investigated. Specifically, the study was limited to existing diversions at flow rates not exceeding the existing capacities. It was already well known that these diversions had produced only minor changes in the median lake levels and therefore had little potential to control lake levels. Furthermore, the study failed to make any significant contribution to the understanding of consumptive use patterns within the basin inasmuch as the DCU results generally agree with consumptive use estimates in the IGLLB study report. The DCU study report is plagued by misstatements in part attributable to the fact that consumptive uses in the United States and Canada are calculated independently using different methodologies. This brings about compounded errors when the consumptive use rates are aggregated for hydrologic evaluation. The international teamwork exhibited in the IGLLB study is absent in the DCU study because of a longstanding policy wherein each country maintains a protective sovereignty over its territorial waters. Both countries avoid any public study that would allow the identification or inventory of specific withdrawals from the Great Lakes tributaries, which technically include all of Lake Michigan.

It is unfortunate that the DCU study did not provide better data. The rate of consumptive use within the basin is nearing a level that will affect the correct interpretation of hydrologic water supply. An accurate inventory of consumptive use is necessary to insure that future additions to the water supply database will be valid. New studies are needed to address this deficiency.

The ILER and DCU studies follow the same general procedure as the IGLLB study in performing the hydrologic and economic evaluations. The methodology consists of three basic components. These are (1) the hydrologic database, (2) the hydrologic evaluation, and (3) the economic evaluation.

The term "hydrologic evaluation" refers to the use of a computer simulation model to calculate the sequence of lake levels that results from a given (usually historically recorded) sequence of water supplies under the imposition of a known set of regulation policies and diversion flows. The hydrologic database established for the IGLLB study was simply extended in time for use in the later studies. "Economic evaluation" refers to the computation of a sequence of costs and benefits that result from a change in the lake levels relative to some basis of comparison. This is actually a two-stage process: the simulation of the activity (e.g., hydroelectric power generation) or impact process (e.g., shore erosion) followed by economic analysis in which a dollar figure is attached to the impact.

The University of Wisconsin Great Lakes Water Management Study

In 1982, the UW Sea Grant Institute initiated a study of Great Lakes water resource management. The findings of this four-year study are presented in this report. The primary objective of the research was to develop policy analysis tools and a framework to aid in making decisions should the demand for competing uses of Great Lakes water increase in the future. In particular, the analysis framework seeks to address the possibility of new interbasin diversions of water from the Great Lakes to neighboring watersheds.

A logical first step toward the design of the proposed analysis methodology was a thorough review of the manner in which current policy was established, which in fact arose out of the IGLLB study. No major changes in the policy resulted from either the ILER or DCU studies. They do, however, represent the most recent applications of the IGLLB strategy; therefore, the results of these studies were also examined. It was determined that the best approach to develop a tool for assessing diversion impacts would be to adapt the models and methods formulated by the trio of IJC study boards to potential future diversion situations.

The remainder of this report is devoted to the description of the most important aspects of the IJC study board methodology and changes introduced by the University of Wisconsin research team. The differences in approach occur either because it is believed that the earlier approach was incorrect or inconsistent or that it needed to be modified in order to address the diversion issue properly. Chapter 2 describes the procedure used to develop the database of water supplies that drives the hydrologic evaluation model. This database is perhaps the single great accomplishment of the IGLLB study. No further hydrologic research was performed by the later study boards beyond extending the series to cover the years since the IGLLB had completed its work. The hydrologic evaluation model is described in chapter 3. A description of current regulation policies for the controlled lakes is also presented. Chapter 4 presents numerical results for a number of potential diversion scenarios. As will be explained, the scenarios and the resulting impacts on lake levels are more or less arbitrary. This is due to an unavoidable ambiguity in the modeling strategy that arises because the postdiversion regulation policy must be specified. For this reason, part of chapter 4 is devoted to an explanation of regulation and modeling parameters that must be adjusted in order to perform valid simulations.

CHAPTER 2

GREAT LAKES HYDROLOGIC DATA

Origin of the Net Basin Supply Approach

There have been many studies of the responses of Great Lake water levels to changing climate conditions. Research concerning expected economic returns based on the annual water supply to the Great Lakes dates to 1911, and the issue has been reexamined frequently since. Studies in 1911 and 1920 (IGLLB 1974, Appendix B, Vol. 1, p. 8) attempted to estimate potential benefits of hydropower production and navigation improvements along the St. Marys River. The data needs for these studies consisted of historical outflows from Lake Superior. Lake level variations were assumed negligible to the extent that any variation could be absorbed using the newly constructed regulatory works.

In 1925, John R. Freeman, an engineer for the Chicago Sanitary District, compiled a comprehensive review and analysis of water supply to the Great Lakes system and the relationships between supplies and flows. His report established a number of precedents worthy of a great deal more attention than Freeman received. The likely reason that his work remains virtually unknown is that Freeman's primary purpose was to defend the continuing and growing interbasin diversion from Lake Michigan into the Illinois Waterway to dilute Chicago's wastewater. The diversion quantity had grown steadily from an inconsequential amount in 1900 to many thousands of cubic feet per second at the time of Freeman's work. Five years later, the U.S. Supreme Court ordered the Sanitary District to cut back the diversion (which had grown even larger in the interim) by 60% to its present average of 3,200 cfs (cubic feet per second) (U.S. House of Representatives 1974, Document 93-47, pp. 33-35). This decision may have cast a further shadow on Freeman's work.

Whatever the reasons, the analyses performed by Freeman were overlooked, and many of his efforts were duplicated 40 years later. He carefully collected all available information on the Great Lakes region; both scientific computations and climatological records were woven into a fine treatise on water level variation on the Great Lakes. He touched upon every conceivable process influencing lake levels. Of particular interest is the methodology Freeman used to establish his conclusions about the cause of low water levels in the 1920s. The work was based on a derived parameter known as net basin supply (henceforth referred to as NBS).

Freeman addressed the need to create consistent measurements of water surface elevations. Great Lakes water levels have been measured daily throughout the basin since 1860. (Streamflow records are complete starting in 1889.) Both flows and levels have been affected by diversion and regulation (U.S. Department of Commerce 1982). By 1925, Lake Superior regulation had been in operation for five years. The Welland Canal and Chicago diversions had been in place for 90 and 25 years, respectively. Thus, none of the available lake level records reflected natural variations of the water levels. Freeman recognized the need to reconstruct, in some manner, a series of supply values exclusive of the effects of human intervention in order that such actions, past or future, might be evaluated.

Approaches to Establish the Hydrologic Database

In more recent studies, two approaches have been used to construct an "unbiased" hydrologic database. Both of these rely on the familiar hydrologic budget as follows:

$$\Delta S = (I-O)\ \Delta t + (P-E)A_l + R\Delta t + G_{net} - D\Delta t. \tag{2.1}$$

Setting Δt to be one month, the following definitions apply:

ΔS =	Monthly change of storage in cfs months ($\Delta S = \Delta HA_l$)
ΔH =	Monthly change of lake level in feet
A_l =	Lake area in cfs months per foot depth
I =	Average monthly mainstem inflow in cfs
O =	Average mainstem outflow in cfs
P =	Direct precipitation onto lake in feet (areal average)
E =	Evaporation from lake in feet (areal average)
R =	Basin runoff in cfs; excludes that portion that enters the lake through the mainstem connecting channel
G_{net} =	Net inflow volume from subsurface fluxes in cfs months
D =	Diversion out of lake in cfs (assumed constant).

In the case of the Great Lakes system, there is no evidence that any of the terms in equation (2.1) may be omitted. The budget may be rewritten as:

$$(P-E)A_l + R\Delta t + G_{net} = \Delta HA_l + (O-I)\Delta t + D\Delta t. \tag{2.2}$$

This version gives rise to the two commonly used techniques for hydrologic evaluation of the Great Lakes, namely rainfall-runoff modeling and NBS (basin yield) analysis. These two methods are equivalent inasmuch as the hydrologist is constructing a parameter given by either the left-hand side or right-hand side of equation (2.2). That is:

$$N = (P-E)A_l + R\Delta t + G_{net} \tag{2.3}$$

$$N = \Delta HA_l + (O-I)\Delta t + D\Delta t. \tag{2.4}$$

The net basin supply, N, is defined as the water volume available to (or taker from) a single lake during the time period, Δt, which is usually taken to be one month. Equation (2.3) expresses this quantity as the sum of natural hydrologic processes occurring during the month in question, and equation (2.4) is written in terms of the response exhibited by the lake during that month. The two approaches to determining basin supply differ only in the given relationships used to compute the monthly values of N.

There is general disagreement over which of the two approaches is more dependable. Both have extensive data requirements and are subject to substantial estimation error. Many literature examples of the rainfall-runof techniques are available (Quinn 1978, pp. 295-307; Croley 1982). The popular reasons for choosing rainfall-runoff analysis over the lake response method include:

1. It addresses the fact that the supply process is composed of a number of stochastic processes.

2. The historical records of precipitation are usually longer and more redundant, in a geographic sense, than those for streamflow or lake level.

3. The model can be calibrated against a known response.

It is apparent that many investigators fail to appreciate the uncertainty associated with converting point measurements of precipitation to areal estimates of precipitation volume. Greater uncertainties are likely to exist in evaporation and runoff estimates. Some key advantages to using the lake response method are:

1. There is less estimation error associated with converting a depth over an area into a water volume.

2. Groundwater contributions need not be neglected as is the case in the vast majority of rainfall-runoff studies.

3. Fewer distinct time series are used to develop the NBS series.

The Great Lakes system is well suited to the lake response method for deriving NBS. The historical record of flows and water levels is long and complete. Diversions must be very large in order to have a significant effect upon lake levels. There are three such diversions within the basin, and all three have been measured during the time period that coincides with the measured series of levels and flows.

As a major component of the IGLLB study, the U.S. Army Corps of Engineers Great Lakes Hydraulics Research Center derived a NBS series for each of the Great Lakes watersheds. Since it is impossible to distinguish between the water levels of Lake Michigan and Lake Huron, the two lakes must be represented by a single net basin supply series. The corps derived distinct series of monthly net basin supplies for Lake Superior, Lake Michigan-Huron, and Lake St. Clair. Quarter-monthly NBS series were derived for Lakes Erie and Ontario. Although Lake St. Clair is minute in comparison to any of the other lakes for which series were developed, its location between Lake Huron and Lake Erie makes it of great hydraulic importance.

For the IGLLB study, the Corps of Engineers worked with the Great Lakes Environmental Research Laboratory (GLERL). Great care was taken in constructing the NBS series from the historical levels and flows. The first 40 years of data (1860-99) were rejected because there were not a sufficient number of water level stations on each lake. Six reporting stations were used on Lake Superior, eight on Michigan-Huron, and four each on Erie and Ontario. Lake St. Clair is not large enough to develop significant surface tilt (setup), so just one recording station was sufficient. Supply data are now available for the period 1900 to 1978. The NBS data set for the Great Lakes is summarized in appendix 2, where means and variances are given for the particular months or quarter-months of the year throughout the 79-year period of record.

The water level records were corrected for systematic errors including isostatic rebound and faulty gage datum levels. In order to measure the change in storage during a given month, the lake level must be known on the first and last day of that month. In a sense this is another areal estimatior problem because the water surface is neither perfectly flat nor horizontal. A system of geographically opposite stations is used to take account of this problem (Quinn, Derecki, and Kelly 1979). If, on a given date, a water level value was not available, the other station in the pair of opposite sites was also not used. A water level based on the average of three daily values was used at each site in order to eliminate the effects of tides and seiches. Despite the fact that this amounts to the use of point estimates to arrive at a volume, it should be noted that errors introduced will cancel out each othe1 from month to month. This is also true of errors due to thermal expansion an(contraction of the water body.

Ample streamflow data were available for the connecting channels. In most cases, flows were measured by both the U.S. and Canada. Lake Superior's outflows have been regulated since 1919. The flow rate through the control structure can be determined quite accurately by rating curves. The same is true of Lake Ontario since 1958, and Lake Erie's outflow through the Niagara River has been measured with care since 1950. The flow measurements before these dates and on channels not mentioned were reasonably good. The IGLLB investigators felt that it was nevertheless necessary to reconstruct the othe flow records to some extent (Department of the Army 1966, pp. 12-13). In particular, they were uncertain about the flow records based on two stage-discharge relationships where one (as opposed to none) of the stages wa a lake elevation. Such records ignored the effects of isostatic rebound, a geophysical process that systematically increases the apparent water levels o southern and western lake shores (Freeman 1925, pp. 149-53). Another problem arose when the rating curves could not be redetermined promptly after major channel dredging operations.

Contributing to the overall supply estimation problem is the effect of ice cover in and near the connecting channel entrances. Ice poses two problems t the modeling effort: (1) it has an impact on the record of historical discharges, and (2) its effects must be included in the simulation strategy. Estimating of ice retardation in connecting channel flows was a necessary component of the Corps of Engineers' effort to reconstruct flow records. Hence, historical series of past ice effects are available for each channel. These data are summarized in appendix 2. The manner in which ice is handled in the simulation procedure is described in chapter 3. The problem has been simplified by the construction of an ice boom in Lake Erie that prevents ice from retarding Niagara River flows. The fact that Lakes Superior and Ontari(are regulated means that ice effects also are nil on these lakes' outlet channels (ILER 1981, Appendix A, Vol. 1, pp. 10-12). Ice effects remain significant on the St. Clair and Detroit rivers as does summertime weed grow in the Niagara River, which has the same sort of impact on the flows there.

CHAPTER 3

HYDROLOGIC MODELING OF GREAT LAKES MANAGEMENT PLANS

Simulation of Great Lakes Water Level Variation

The simulation model employed in hydrologic evaluation of Great Lakes management policies is divided into three components. Within the entire hydrologic evaluation model there are distinct models describing the processes of:

1. Great Lakes hydrology
2. connecting channel hydraulics
3. outflow regulation.

The majority of the computational effort is devoted to the simulation of the regulation plans currently used to specify outflows from Lakes Superior and Ontario. The general approach to the simulation is diagrammed in figure 1. Lake Superior level and flow are determined first; computations continue in the downstream direction from there. The so-called "middle lakes" must be dealt with as a group because their water levels are interdependent. Lake Ontario, on the other hand, is, in the hydraulic sense, independent of all other levels or flows upstream of Niagara Falls. This means that the upper lakes can be simulated without referring to any Lake Ontario computations, at least under current regulation policies.

The basic time step used in the model is one month for Lake Superior and one quarter-month for the remaining lakes. The basic time step is divided into 10 substeps whenever Lake St. Clair is directly involved in the calculation. Because Lake St. Clair is the middle "middle lake," all computations involving the middle lakes use a time step equal to one-fortieth of a month. Regardless of the size of the time interval, there is also a fixed number of computation iterations within each step.

Each simulation "month" begins with known water levels and connecting channel flowrates for all five lakes. These are denoted as BOM levels and flows. The first procedure undertaken in the model is determining the desired regulated outflow for Lake Superior. The current regulation policy is called Plan 1977. The details of operational procedures contained in Plan 1977 are described later in this chapter. The outflow from Lake Superior is controlled at the head of the St. Marys River by a series of 16 gates that span the entire channel. The structure is known as the compensating works, so named because the majority (80%) of Lake Superior outflow is diverted to hydroelectric facilities located on either side of the river channel. Thus, the objective of the Lake Superior regulation sequence is to determine what additional flow should be passed through the compensating works.

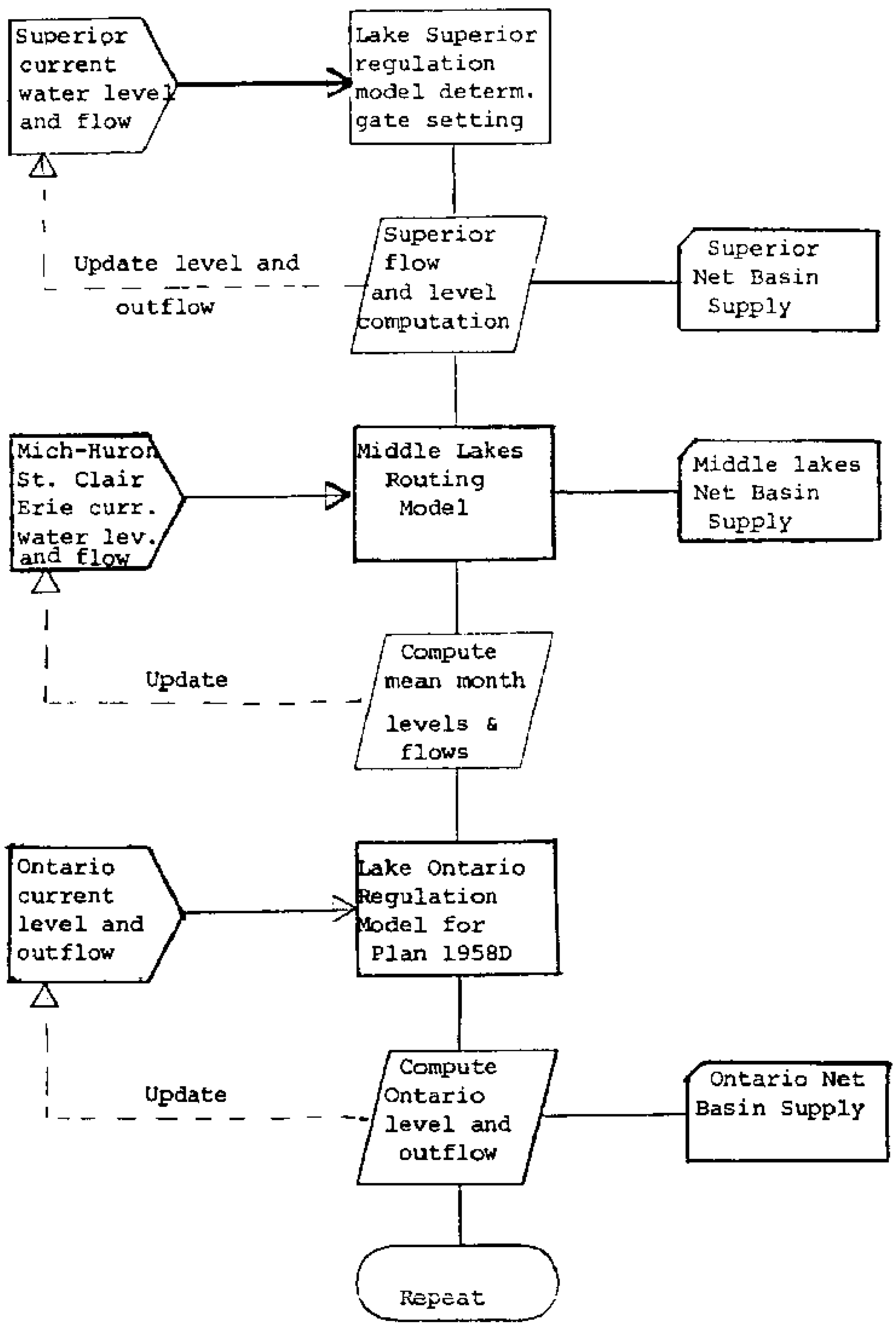


Figure 1. Great Lakes regulation and hydrologic response simulation model

The current treaty allows for diversion of 65,000 cfs for power generation, equally split by power companies from each nation. Under certain low water conditions, the guarantee (in fact, the allowable outflow) is reduced to 55,000 cfs. A set of rating curves is available that describes the relationship among the Lake Superior water surface elevation, the number of gates raised in the compensating works, and the flow through the works. This family of curves is shown in figure 2. With one exception, there is no provision for partial opening of the gates. Therefore, the outflow cannot be dictated over a continuous range, although the behavior of Lake Superior does not really warrant a greater level of control. Once the desired outflow rate has been determined, the gate setting (the number of open gates) that provides for an outflow rate closest to the desired flow can be computed. The Superior outflow computation subroutine is designed to determine the outflow for a given combination of gate setting and water surface elevation or the gate setting for a given outflow-elevation combination. This subroutine is based on empirical formulations of the rating curves given in figure 2. The gates are not usually moved during the winter season. The gate settings are currently determined on the first day of each month, beginning with May. The gates are set for the entire winter on December 1.

Once the regulation procedure is executed, the actual response of Lake Superior is determined by means of a mass balance. The Superior NBS for the current month is converted to an equivalent depth over the area of the lake and added to the beginning-of-month (BOM) water surface elevation. The outflow is similarly converted to a depth, which is subtracted from the elevation obtained in the previous step. The result is the first cut at obtaining a value for the end-of-month (EOM) lake level. A mean lake level for the month is approximated by averaging the BOM and EOM levels, and is used, in turn, to compute what is assumed to be a mean outflow for the month. This procedure is repeated three times, invariably converging by the end of the fourth iteration. Under the greatest extremes of supply and outflow, the Lake Superior water level might change 0.40 feet in a given month; however, the normal is about 0.18 feet. The small monthly variation exhibited by Lake Superior is the reason convergence is assured after four iterations; it also permits the assumption that the mean level yields the mean flow rate and that it is appropriate to use the mean outflow in subsequent computations involving Lake Michigan-Huron. The mean Lake Superior water level has no further effect on simulation calculations; it is simply saved for the output file. The EOM water level and flow become BOM information for the following time step.

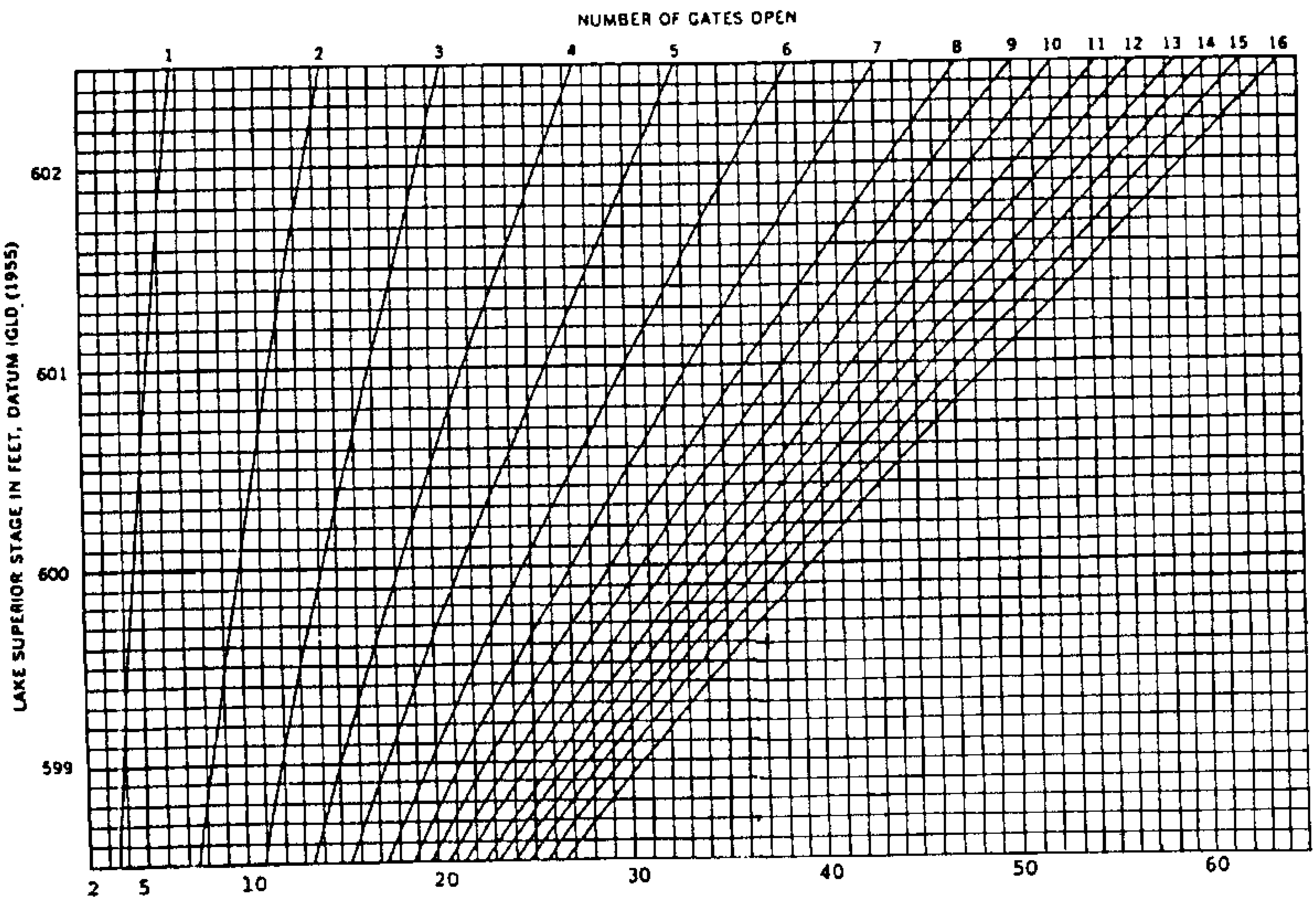


Figure 2. Compensating works discharge as a function of Lake Superior water level and the number of gates raised (Source: International Great Lakes Levels Board 1973)

The next procedure in the model, called "middle lakes routing," is the computation of the levels and flows for Lake Michigan-Huron, Lake St. Clair, and Lake Erie. These lakes must be considered as a group because flow in their connecting channels, the St. Clair and Detroit rivers, depends on both upstream and downstream lake levels. That is, the instantaneous flowrate of the St. Clair River is a function of the water surface elevation of Lake Michigan-Huron and Lake St. Clair, and the flowrate of the Detroit River depends on the elevations of Lake St. Clair and Lake Erie. Since Lake Erie elevation depends on its own outflow through the Niagara River, this flow information also must be available. In essence, this amounts to a hydraulic routing problem that has six unknowns per time step: three elevations and three outflows. Six equations relating these unknowns can be constructed by writing hydrologic budgets for each lake and hydraulic resistance formulae for each channel.

There are a number of options available from which to select a relationship describing the steady nonuniform flow of the St. Clair and Detroit rivers. The hydraulic relationship used in the model is empirical (GLBC 1975-76, Appendix 11, p. 56), but it is similar to the theoretical formula for flow over a submerged, broad-crested weir:

$$Q = C' \, A \, H^{\frac{1}{2}} = C'' \, B \, y \, H^{\frac{1}{2}} \tag{3.1}$$

Here, A and B are the area and average width of the flow, y is the mean or effective depth, and H is the effective upstream head. C' and C'' are distinct constants that depend on channel shape and roughness as well as the system of measurement units. In figure 3, the depths h_1 and h_2 can be chosen so that the following expressions are approximately correct:

$$y = \frac{(h_1 + h_2)}{2} \tag{3.2}$$

Assuming that the width of flow is a linear function of depth leads to the flow formula used in the middle lakes model:

$$Q = C \left(\frac{h_1 + h_2}{2}\right)^2 (h_1 - h_2)^{\frac{1}{2}} \tag{3.3}$$

Equation (3.3) is commonly called a two-stage discharge relation. In any of these forms, the constant, C, is determined by a fitting technique.

The flow relations used in the model are listed in appendix 3. Niagara River flow is assumed to be free flow through a critical section, hence it can be written as a function of a single gage height raised to the 3/2 power.

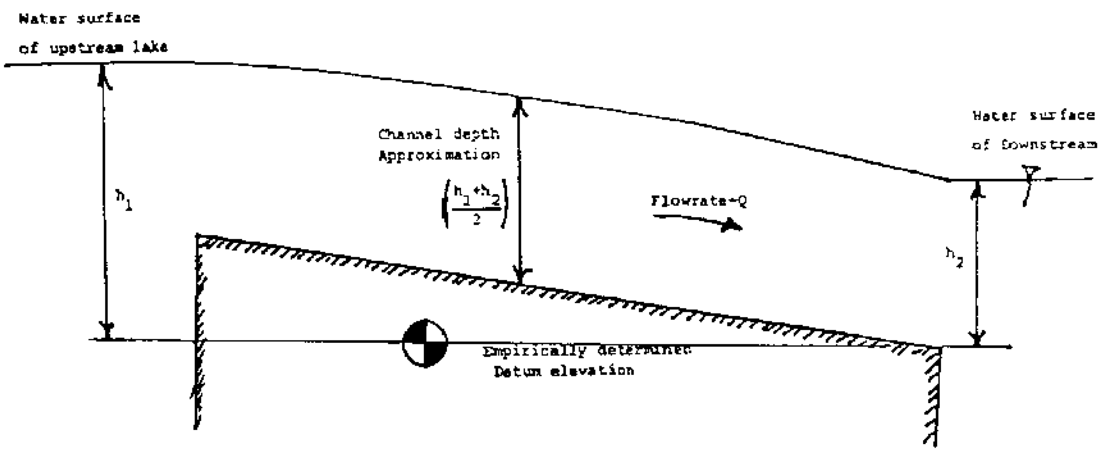


Figure 3. Definition sketch for development of two-state flow relations

The middle lakes routing model consists of six equations that are solved in the following sequence. The net total supply (NTS) to Lake Michigan-Huron is its NBS plus the mean outflow of Lake Superior minus the diversion flow into the Chicago sanitary and ship canal. At present, this diversion is approximately 3,200 cfs and exhibits little monthly variation, according to the Corps of Engineers, which is responsible for its measurement. In contrast, the water supply diversions for Detroit, Michigan, and London, Ontario, are ignored, although up to 1,200 cfs are withdrawn from Lake Huron (GLBC 1975-76, Appendix 11, p. 56). This water is returned to Lake Erie after bypassing Lake St. Clair and the two connecting channels.

The routing system is solved 40 times per monthly time step. In each substep, one-fortieth of the Michigan-Huron NTS and Lake St. Clair NBS and one-tenth of the quarter-monthly NBS to Lake Erie are converted to changes in storage and added to the levels of each lake. The resulting lake levels are used to compute outflows for each lake, with appropriate adjustment made to each lake level according to the difference between inflow and outflow. The Welland Canal diversion of 7,000 cfs is assumed to be a constant addition to the Lake Erie outflow.

The preceding level and flow computations are repeated three times per substep to assure convergence. At the end of each substep, end-of-period (EOP) flows and levels are saved for later computation of quarter-monthly and monthly means.

Having completed the middle lakes routing, the simulation advances to the next month, returning to the computations associated with regulation of Lake Superior, unless the current month is December. In this case, the model proceeds with 12 months of Lake Ontario simulation. Because Lake Ontario is by and large independent of the upper lakes, the computations for this lake could be delayed until the upper lakes modeling is completed for every year in the simulation run or, if desired, ignored altogether.

The present Lake Ontario regulatory policy is known as Plan 1958D. In contrast to the releases from Lake Superior, it is possible to adjust the release from Lake Ontario continuously. It is thus possible to specify a precise outflow. Lake Ontario NTS is the sum of its NBS, the Welland Canal flow, and the Lake Erie outflow (into the Niagara River). The outflow rate specified by Plan 1958D may be subtracted directly from the NTS to yield the quarter-monthly change in storage. This volume is converted to a change in lake level, thus completing the hydraulic simulation of Lake Ontario. Note that no iterative procedure is needed.

Structure of Regulation Plans

In general, a Great Lakes regulation plan is a procedure for determining the desirable outflow rate from a controlled lake for a definite future time period. This flowrate must be singularly defined by current or past conditions based on parameters such as lake level, flows, or supplies. The time of year often plays an important role in outflow determination. The simplest format of a proper regulation plan gives the regulated outflow as a function of current lake level only. An example of this type of plan is the Modified Rule of 1949, which was used to determine Lake Superior outflow during the 1950s and 1960s (IGLLB 1974, Appendix G, pp. 14-16). The entire plan is illustrated in figure 4. The figure shows an outflow for every

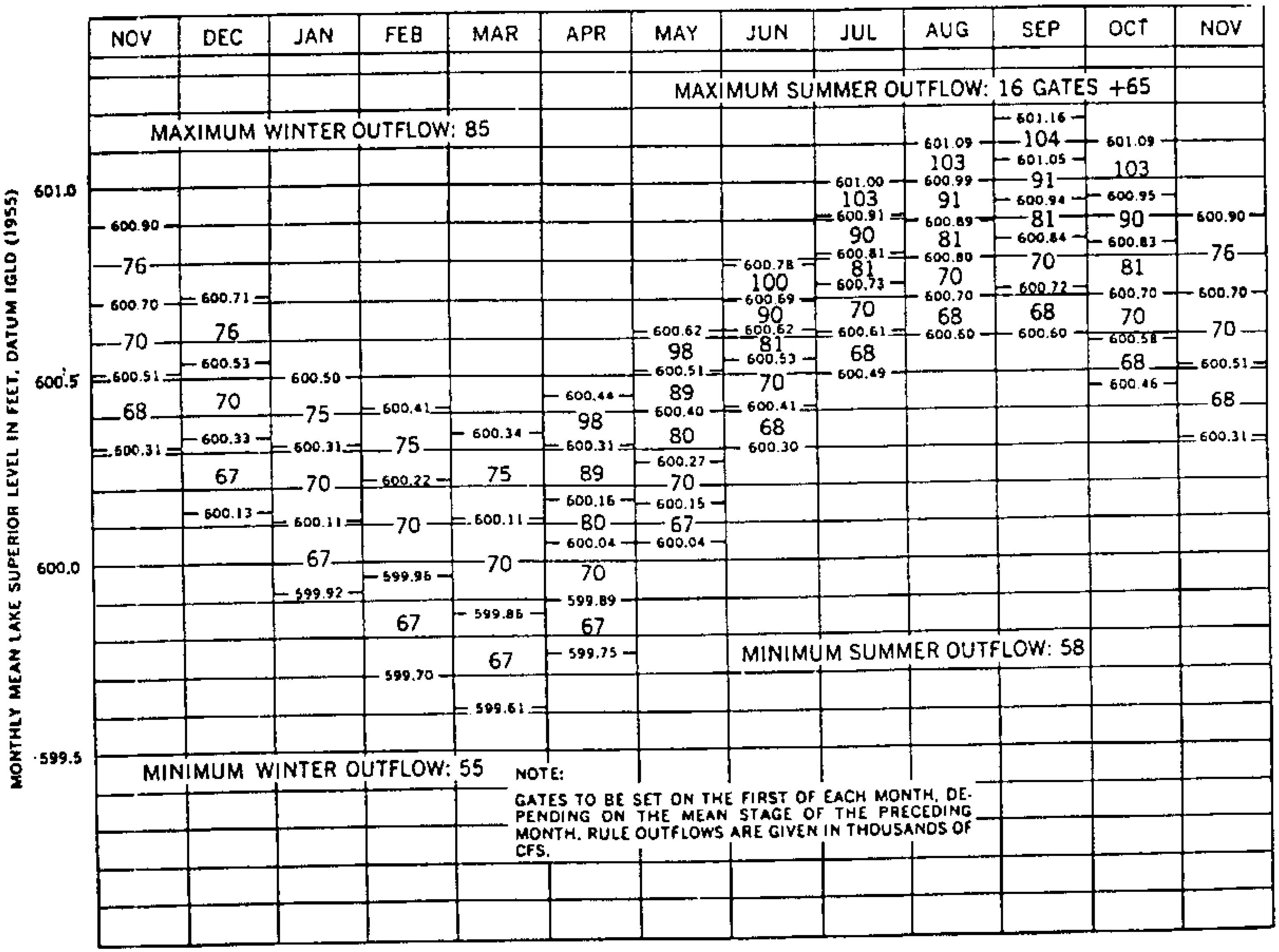


Figure 4. Lake Superior regulation according to the 1955 Modified Rule of 1949 (Source: International Great Lakes Levels Board 1973)

possible combination of water surface elevation and month of the year. The actual monthly outflow will differ slightly in most cases due to physical limitations of the regulatory works and the effect of lake level change during the month. As mentioned earlier for the case of Lake Superior, one physical limitation is that each of the 16 gates is either fully open or completely closed. Once an outflow has been selected, the gate setting that most nearly yields the selected outflow is determined. There is one exception to the gate opening rule. A gate setting in which only one gate is raised halfway is permitted. This is used as an alternative to having no gates open, a situation that is not permitted. The minimum allowable flow through the compensating works is the flow with one gate half open. The rule requiring a whole number of open gates allows the stage discharge relation for flow through the compensating works to be known at all times.

An important recommendation of the IGLLB study was the design of a regulation plan in which the downstream level of Lake Michigan-Huron as well as the Lake Superior water level would be taken into account. This would presumably limit the extent of adverse impacts to all of the middle lakes. Regulation Plan 1977 is the most recent update of the final recommendation of the IGLLB plan called SO-901. SO-901 was implemented in 1973 as an emergency replacement to the 1955 modified rule of 1949. Plan 1977 formally replaced SO-901 in October 1979 (International Lake Superior Board of Control 1981, pp. 9-13). Like SO-901, Plan 1977 retains the earlier objective of emulating natural Lake Superior outflows (with adjustment for the Long Lake-Ogoki Diversion). However, it also utilizes the current Lake Michigan-Huron elevation to some degree. It has never been clear whether the stated objectives used to design the regulation plan are being fulfilled in reality. Critics claim that Plan 1977 tends to maintain a Lake Superior elevation in the upper half of its natural range. This assertion has some basis if one examines the economic evaluation structure that has been used in the design and evaluation of prospective policies by various IJC study boards. Results of past studies show a substantial accumulation of benefits when the water level regimes of Lakes Michigan-Huron and Erie are reduced. This is a natural result of higher property values and levels of development per mile of shoreline on these lakes. In turn, this leads to a greater total benefit per foot of water level lowering. If the excess water volume generated by the lowering of the middle lakes is stored in Lake Superior, very little adverse impact is realized because of the traditional economic evaluation technique. Storage of the excess water in Lake Superior benefits both hydropower and navigation on the St. Marys River, and it has virtually no effect on the generation of power at Niagara Falls. Because most shipping routes that pass through the Detroit and St. Clair rivers also use the Welland Canal, commercial shipping also feels little adverse impact from lower middle-lakes levels (GLBC 1975-76, Appendix C9, pp. 81-91). This is because the most severe draft limitation to commercial navigation occurs along the Welland Canal.

The obvious outcome of the economic evaluation structure used by many researchers is a policy recommendation that uses Lake Superior as a vast storage reservoir. Unfortunately, such a recommendation is based on extensive shoreline property benefits, which probably cannot be substantiated in the long run (U.S. House of Representatives 1973, Document 93-8, p. 63).

Procedure for Determining Lake Superior Outflow Using Plan 1977

The gate setting and regulated outflow from Lake Superior are determined on the first day of every nonwinter month. For this purpose, the winter months are January, February, March, and April. In order to reduce the annual number of gate movements, the procedure includes a predicasting operation in which pseudo-predictions of future months' gate settings are determined. ("Predicast" is a contraction of "predicate forecast" and refers to a prediction based on the occurrence of mean-valued phenomena. Such forecasts depend only on the current value of a single-state variable.)

During nonwinter months, the predicasts are carried out through the following November, whereas the December 1 gate setting is based on predicasts extending through April. In either case, the selected gate setting is the average of all of the predicast gate settings rounded to the nearest integer value.

The following procedure generally describes the method for determining the gate setting for a single month under Plan 1977. A detailed description of sequential plan calculations is given in appendix 4.

1. A basic "rule flow" is determined based on the deviation of Lake Superior and Lake Michigan-Huron elevations from the desired levels for a particular month. The function used to compute the rule flow is known as the balance equation.

2. The rule flow is compared to the various minimum and maximum flow limitations. Of course, if any of these limits are violated, the appropriate limitation becomes the new prospective outflow.

3. The gate setting that most nearly matches the outflow indicated in the previous step is determined from the rating curves corresponding to the 17 permissible gate settings shown in figure 2.

Once the gate setting for the current month is determined, Plan 1977 calls for the predicasting of the following month's gate setting. This predicast is based on forecasts of lake level and flow derived from the occurrence of median NBS on each lake basin. The middle lakes routing routine described previously in this chapter is used to forecast the levels and flows needed to determine the following month's gate setting. The gate setting directly depends, however, only upon the level of Lake Michigan-Huron. Once the predicast of the Michigan-Huron level has been computed, a corresponding prediction of the future gate setting is made using the procedure described in steps 1, 2, and 3.

Lake Ontario Regulation According to Plan 1958D

The procedure employed to determine outflows from Lake Ontario is more complex than that of Plan 1977 for Lake Superior. This is because of a number of factors, the foremost being the greater volume of flow involved and the higher intensity of economic development in the region just downstream of the outlet. The Lake Superior outlet channel, the St. Marys River, is 70 miles long with a total fall (elevation drop) of 21 feet. The Lake Ontario outlet channel is the St. Lawrence Seaway, which has a fall of 225 feet over a distance of 103 miles. This large fall is utilized for the production of hydropower in three drops, effectively turning the river into a series of three artificial lakes. For optimal power production it is important that the levels of these pools remain stable without wide fluctuations in the outflows. The Lake Ontario regulatory policy must therefore be designed to anticipate times with a need for increased outflows and thus avoid the use of emergency procedures to compensate for unusual conditions.

Regulation Plan 1958D is a minor variation of the original Plan 1958A, which was implemented upon completion of the St. Lawrence Seaway in May 1958. Minor changes were made to the policy leading up to the implementation of the fourth plan in the series in the fall of 1963 (International St. Lawrence River Board of Control 1963). Plan 1958D specifies only the Lake Ontario outflow. However, this decision may depend on certain downstream conditions. In particular, the outflow from Lake St. Louis can be a factor. This reservoir receives considerable inflow from the Ottawa River, which is outside the Great Lakes Basin and therefore quite independent of the Lake Ontario releases. The structure used to regulate Lake Ontario is the Iroquois Control Dam, located 30 miles downstream of the 1,000 Islands Region, the traditional divide between lake and seaway. This control structure consists of 32 50-foot sluice gates, which permit unlimited control of the flow over a wide range. The capacity of the structure is unknown, but it is well in excess of the currently allowed maximum flow of 310,000 cfs.

In order to meet various requirements of hydropower and navigation, it is necessary to determine a new regulated Lake Ontario outflow four times per month. Thus, the procedure for Plan 1958D is repeated 48 times per year, and it is necessary that all plan parameters be available on a quarter-monthly basis. The 48 periods per year are referred to by name and number; January 1 is the first quarter-month period of the year, January 2 the second, and March 2 is the tenth.

Plan 1958D has three components that result in three basic steps leading to the eventual determination of the rule outflow. The plan consists of (1) an adjusted supply indicator, (2) basic rule curves for outflow, and (3) maximum and minimum outflow limitations. A detailed description of the procedure used to determine the regulated Lake Ontario outflow is given in appendix 5.

The adjusted supply indicator is a measure of recent supply conditions; it is loosely related to the four-month mean net supply minus the normal value of this weighted mean derived for the plan. The supply indicator is adjusted slightly to prevent overcompensation when the indicator is changing rapidly. There are two basic rule curves, one for February through July, and the other for August through January. The appropriate rule curve is used to determine the Lake Ontario outflow as a function of the value of the adjusted supply indicator and the Lake Ontario water level. This rule flow is subject to several maximum and minimum outflow limits. Some of these limits are a function of the supply indicator.

CHAPTER 4

SIMULATION OF DIVERSION EFFECTS ON WATER LEVELS

Basic Principles of Diversion Simulation

The structure of the Great Lakes hydrologic response model was initially designed to assess differences in water level regimes brought about by various regulatory policies, principally those for Lake Superior. In more recent studies, other features have been added to the model, including a provision for the regulation of Lake Erie and a mechanism for the increase or decrease of existing diversion flows (e.g., at Chicago) based on supply trends and lake level. A key undertaking of the research described in this report was the adaptation of the hydrologic response model to provide a capability for evaluating large-scale diversions of Great Lakes water. A large-scale diversion is distinguished from current diversions by its significant impact to levels and flows in the Great Lakes system.

Part of the mission of the DCU study was to evaluate the effects of water diversions already within the basin. This study board reached the same conclusion given in both the IGLLB and GLBC reports, namely that impacts from current diversions are minimal if not negligible. There are three reasons why such a conclusion would be expected. First, one of the diversions brings water into the system at a most opportune location, Lake Superior. Since the flow enters upstream of a major control structure, it is possible to utilize the added water to its greatest regulatory advantage. The second factor is that regulation policies have been devised to minimize the effects of the existing diversions. In particular, the plans have been designed to meet the objective of no impact to both Lake Superior and Lake Ontario (IGLLB 1974, Appendix A, p. 45). The third reason why present diversions have no significant impact derives from the relative magnitude of the existing diversions compared to the net total supply (NTS) entering those lakes where water is diverted. No existing Great Lakes diversion out of a basin exceeds 4% of the NTS to the associated lake. The diversions postulated in the work described here, on the other hand, would result in impacts of sufficient magnitude to warrant major adjustments in the evaluation framework to allow reasonable comparisons between the current situation and what would be experienced from permanent, large-scale diversions.

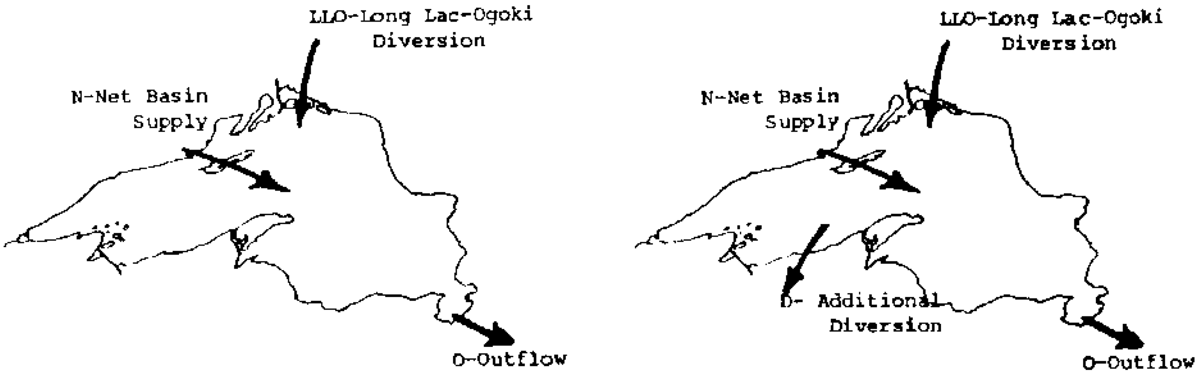
Because of the significant changes to the lake level regime from large diversions, regulation policies would need to be modified to account for reduced net total supplies to the lakes downstream of the point of diversion. Furthermore, the initial lake levels specified in the simulation analysis must also reflect expected changes in the long-term mean water levels. Failure to address this important factor results in model outputs for the first 10 to 15 years of the simulated time period that are not representative of the actual hydrologic impacts, hence it leads to errors in subsequent economic analyses. In the following pages, the justification for appropriate parameter adjustments is presented along with the methodologies for determining the magnitudes of these adjustments. In chapter 4, simulation results are presented for a base case and eight hypothetical diversion scenarios. The base case represents a projection of the current regulatory situation over the entire period of historically measured record of the Great Lakes. It assumes continuation of diversions in place as of September 1981, the completion date of the most recent IJC Study Board investigation.

Parameter Adjustments for Obtaining Realistic Simulation Results

The importance of correctly choosing regulation plan parameters for hydrologic evaluation of diversion proposals will be illustrated with an example based on Lake Superior hydrologic information. As previously discussed, Lake Superior has no mainstem inflow; supply to the lake comes only from dispersed sources. The outflow of Lake Superior is controlled by the St. Marys River compensating works. It is assumed throughout this report that the Long Lac-Ogoki diversions from the Albany River Basin continuously add 5,000 cfs to the Lake Superior NBS. Consider the two cases depicted in figure 5. One assumes no additional diversion; the other, a situation in which 10,000 cfs are continuously withdrawn for use outside the Great Lakes Basin. The first case, of course, represents the present conditions, and the applicable regulation policy is Plan 1977. The plan is designed to maintain a stable lake level regime. In other words, water level fluctuations possess a stationary distribution so that mean water level shows no significant variation through time. The long-term mean outflow, according to the plan, must equal the long-term basin supply in order to achieve this objective. Therefore, Plan 1977 is constructed so that the long-term mean outflow for the current month is the selected outflow when the elevations of both Lakes Superior and Michigan-Huron are at the target elevations specified for each month. The greater the total deviation of the lake levels from their targets, the greater the deviation of the outflow from its historical mean.

In the case where a 10,000-cfs diversion is imposed, it obviously is necessary to reduce Lake Superior outflows, on average, by the same 10,000 cfs. Since Lake Superior is fully regulated, it is possible to design a policy that does not change the lake level regime. Impacts on the unregulated lakes, however, are unavoidable because the throughflow to these lakes has been reduced by 10,000 cfs. In the case of Lake Michigan-Huron the mean outflow of 187,000 cfs is reduced by 6%. Since level and outflow are functionally related for this lake, a drop in lake level is the necessary consequence.

The same situation holds true for Lake Erie. In fact, the approximate impact on the long-term elevation of Lake Erie can be computed easily from the outflow relationship constructed for the Niagara River (see appendix 3). By plugging in the Lake Erie mean outflows corresponding to diversion and no diversion conditions (195,000 and 205,000 cfs, respectively), a resulting approximate impact of 0.48 feet is obtained. Using an iterative process, expected lake level impacts may be obtained for the other unregulated lakes in a similar manner. This direct computation is not entirely valid because the expected value of a function is not the function evaluated at the expected value of its parameters; nevertheless, it agrees quite closely with results obtained through simulation.



Current situation

N = 71 tcfs
LLO = 5 tcfs
O = 76 tcfs

With a new 10 tcfs diversion

N = 71 tcfs
LLO = 5 tcfs
D = -10 tcfs
O = 66 tcfs

Figure 5. Water balances for Lake Superior based on long-term mean supply

Considering once again the levels of Lake Superior, it can be demonstrated that it is practical to impose lake level reductions on this lake. When Plan 1977 target levels are used in simulations of Lake Superior diversions, the resulting water level regime has increased variance in comparison to the same policy with no diversion. Reduced Lake Superior target levels may be employed to achieve a variance structure for resulting time series of lake levels similar to that obtained in simulation without water diversion. In the latter situation, however, the overall mean water levels are lower.

In addition to the downward adjustment of regulated outflow and target levels contained in regulation plan operating procedures, it may also be necessary to decrease the lower limit(s) imposed on outflows in order to obtain a realistic series of levels. Figure 6 illustrates the problem that might develop when the minimum allowable outflow remains at the prediversion value. This occurred during an extended period of low supply experienced in the Lake Superior watershed during the late 1920s. The series shown is the simulation result obtained using a version of Plan 1977 in which the target flows and levels were reduced by appropriate amounts to accommodate a diversion of 10,000 cfs. The minimum Lake Superior outflow is set at the rate guaranteed for hydropower use in a 1914 order of the IJC (International Lake Superior Board of Control 1981, Appendix A). The graph depicts the amount of water level reduction caused by the continuous diversion of water from Lake Superior

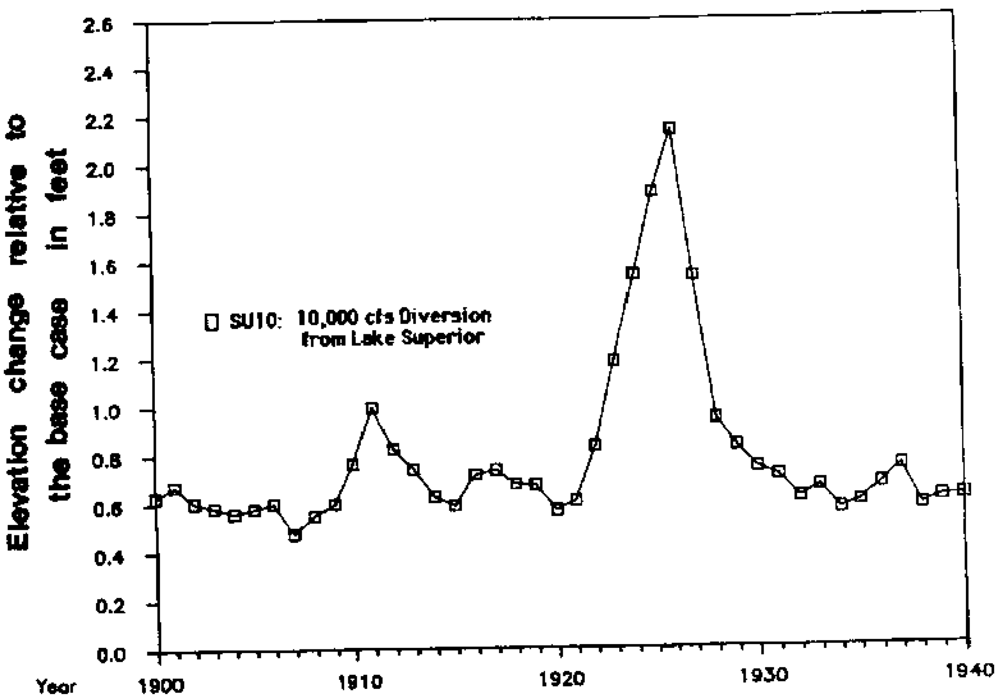


Figure 6. Reduction of Lake Superior level under Scenario SU10

given the net basin supplies that occurred during the first 40 years of the twentieth century. The major low-water event that occurs in the 1920s can be attributed to the hydropower guarantee. When the guaranteed flow is reduced, the unusual event is eliminated.

Another parameter important for accurate hydrologic evaluation of diversion scenarios is the initial lake level, that is, the water surface elevation assigned to each lake at the beginning of the time period to be simulated. Because the water level is certain to seek a new mean value through time, it would be incorrect to use the same initial level for scenarios that have different diversion flows. Figure 7 gives the results of two simulations of 10,000-cfs diversions using different initial conditions. This graph shows net change in Lake Superior water levels through time relative to the base case (in which there is no additional diversion). The initial condition for one of these runs is identical to the initial condition for the base case (600.51 feet).

This series begins with very small lake level reductions that grow steadily for about five years and eventually converge with the other series. Different choices of initial level will lead to a series that converges in the same manner as the example within 15 years. In the present research effort, the long-term mean levels for all lakes for the month of December were used as the initial conditions in all simulation runs (computations begin with January).

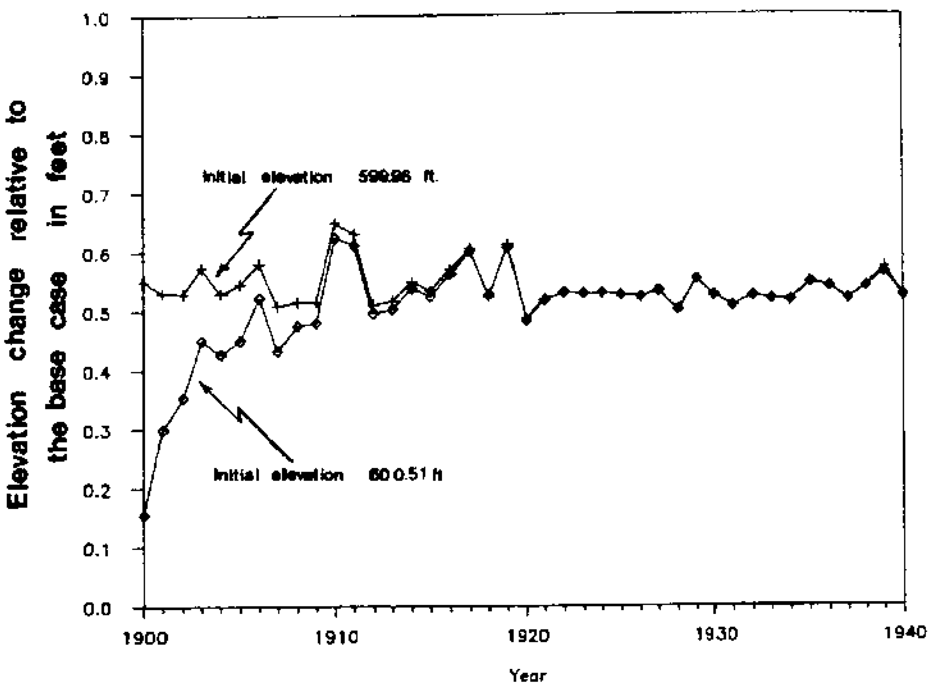


Figure 7. Reduction of Lake Superior level under Scenario SU10L

These long-term means were determined iteratively for the diversion scenarios modeled by repeating the simulation process for two or three different sets o initial levels and noting the long-term mean levels for December indicated by the output time series.

Diversion Scenarios

In the investigation, eight scenarios of hypothetical diversions of water fro the Great Lakes Basin were devised for evaluation. In addition, there is a base-case scenario in which no additional water diversion was imposed. In every one of the scenarios, all existing major diversions were assumed to continue at their present flowrates. The existing diversions are: the 5,000 cfs flowing into Lake Superior from Long Lac and the Ogoki River, the 3,200 cfs out of Lake Michigan at Chicago, and the 7,400 cfs to the Welland Canal. The flow used to maintain navigation in the Welland Canal diversion is in effect a diversion out of Lake Erie and into Lake Ontario, thus it lowers th level of the former. Additional diversion flows were imposed as identified i the scenarios listed in table 4. The identifying codes given in table 4 wil be used throughout the remaining pages of the report to refer to the differe scenarios.

TABLE 4. Scenario identification labels and associated flows

Scenario ID	Diversion Flow	Lake Diverted From
Base Case	0	----
SU5	5,000 cfs	Superior
SU10	10,000 cfs	Superior
SU10L	10,000 cfs	Superior
SU30	30,000 cfs	Superior
MH10	10,000 cfs	Michigan-Huron
MH30	30,000 cfs	Michigan-Huron
ER10	10,000 cfs	Erie
ER30	30,000 cfs	Erie

The research objectives of our study were primarily concerned with developing appropriate methodologies for the analysis of potential diversion impacts. Less emphasis was placed on identifying likely diversion strategies that might be employed, much less on determining economically feasible routes or demand locations. Therefore, the quantities of water selected for the diversion scenarios are based on factors not tied to any specific proposal or demand projection. Rather, the diversion flows were selected so the magnitude would be sufficiently large to pose the possibility of significant impacts on users of Great Lakes water. Previous studies considering diversion effects have limited themselves to additional interbasin transfers at flows ranging between 3,200 and 10,000 cfs. They were responding largely to one specific and widely discussed proposal: In 1974, the Corps of Engineers sought congressional authorization to increase the Chicago diversion by as much as 6,800 cfs during periods of excessively high water levels on Lake Michigan (U.S. Army Corps of Engineers 1981). The proposal was apparently studied and rejected largely because of the flooding threat it would create along the receiving waterways.

Results from previous research have shown that a 10,000-cfs diversion is large enough to change appreciably the water level and flow regimes throughout the system. At the same time, a diversion of this magnitude falls well within the range of flows that are feasible from an engineering standpoint (DeCooke, Bulkley, and Wright 1984, pp. 6-11) and perhaps from a political standpoint as well. Four of the scenarios listed in table 4 involve diversions of 10,000 cfs. This rate was used repeatedly to facilitate comparison among the different diversion situations. A method was sought to weight the virtue of using one lake over another as the source and to assess the validity of certain changes in policy.

Four scenarios use flowrates other than 10,000 cfs. The SU5 scenario was devised to compare this research to the results obtained in the DCU study. The DCU Study Board investigated the impacts that would occur if the Long Lac-Ogoki (LLO) diversion were shut off, eliminating 5,000 cfs from the supply to Lake Superior. Since the base case in the present research includes the incoming LLO diversion, an additional outgoing diversion of 5,000 cfs would have the identical effect of the DCU scenario. An opportunity is thus provided to examine the influence of the parameter changes described previously on the simulation outputs. The other rate used is 30,000 cfs, a quantity viewed as approaching the upper limit for feasible large-scale diversions. An example of such dimensions is a major diversion project nearing completion in the Soviet Union. Here, water is transferred from the Pechora River to the Volga Watershed by a conveyance system with a nominal capacity of 1,000 cubic meters per second (35,000 cfs) (Lvovich 1969 & 1973, pp. 187-190). Diversions of still larger quantities are being contemplated in both the Soviet Union and North America.

Information is given in table 5 on the adjustments to regulation plan parameters that were specified for the simulation of the various scenarios. Initial lake levels used in the simulations are among the data listed in table 6.

TABLE 5. Plan 1977 parameter changes used in simulation runs

Scenario	Superior Target Stage (ft)	Michigan-Huron Target Stage (ft)	St. Marys R. Target Outflow (cfs)	Absolute Minimum Outflow (cfs)
SU5	-0.30	-0.35	-5,000	-5,000
SU10	-0.50	-0.65	-10,000	0
SU10L	-0.50	-0.65	-10,000	-10,000
SU30	-1.80	-2.00	-30,000	-30,000
MH10	-0.25	-0.70	0	0
MH30	-1.00	-2.10	0	0
ER10	0	-0.20	0	0
ER30	-0.25	-1.30	0	0

TABLE 6. Initial lake levels used in the simulations

Scenario	Superior	Michigan-Huron	St. Clair	Erie
Base	600.51	577.78	572.80	570.00
SU5	600.30	577.58	572.80	570.00
SU10, SU10L	599.98	577.38	572.40	569.52
SU30	598.70	576.45	571.40	568.50
MH10	600.27	577.35	572.40	569.52
MH30, ER30	599.98	576.45	571.40	568.50
ER10	600.40	577.58	572.40	569.50

Simulation Results

The simulation model outputs may be presented in a variety of ways. The actual outputs consist of mean values of all connecting channel flowrates and water levels at various basin locations. These are provided on a monthly basis for each period in the 79-year span for which input data are available. A complete list of outputs available from each run is provided in table 7. These monthly series serve as the basic inputs to the simulation models used in the economic analyses.

TABLE 7. Monthly output data available for further analysis from the Great Lakes hydrologic response model

1. Lake Superior elevation
2. Lake Superior outflow
3. Lake Michigan-Huron elevation
4. Lake Michigan-Huron outflow (St. Clair River)
5. Lake Erie elevation
6. Lake Erie outflow (Niagara River and Welland Canal)
7. Lake Ontario elevation
8. Lake Ontario outflow (St. Lawrence River at Cornwall)
9. Lake St. Clair elevation
10. Lake St. Clair outflow (Detroit River)
11. St. Marys River compensating works gate setting
12. U.S. slip elevation (on St. Marys River below compensating works)
13. Lake St. Louis elevation (approximate)
14. Lake St. Louis inflow (combined St. Lawrence and Ottawa rivers)

They are not, however, particularly useful for the presentation of hydrologic effects without first performing some data reduction. This is mainly because of the seasonality inherent in lake level variations that are independent of diversion effects. The simulation results that are of greatest general interest are the changes in water level caused by diversion, in other words, the amounts by which water levels decrease. These quantities are obtained by subtracting water levels determined in a diversion scenario from those in the base case. The procedure assumes the base case is representative of current policy and channel conditions. The base case used in the present study is compared to those employed in previous work in table 8. It is clear that the range of values is limited. Water levels from the IGLLB study tend to be lower because the study was completed before the high-water period in the early 1970s.

Water level impacts relative to the base case are presented in table 9. Impacts on Lake Ontario have been omitted for a variety of reasons. For one thing, they would be more or less arbitrary because Lake Ontario's water level is independent of the upper lakes' water levels and heavily dependent upon the regulation policy employed at the lake's outlet. In any case, the reduction in Lake Ontario elevation would not depend on the lake from which the withdrawal occurs. This is also true of Lake Erie.

TABLE 8. Mean lake levels: comparison of historical means to base cases from various studies

Lake	Historical 1900–1980	Base Case	IGLLB-BOC	DCU-BOC
Superior	600.57	600.47	600.38	600.44
Michigan-Huron	578.20	578.27	577.95	578.27
Erie	570.35	570.77	570.60	570.76
Ontario	244.69	244.75	244.53	244.73

BOC = Basis of Comparison

TABLE 9. Change in average water level relative to the base case (in feet)

Scenario	Lake Superior	Lake Michigan-Huron	Lake Erie
SU5	-0.22	-0.35	-0.22
SU10	-0.71	-0.69	-0.45
SU10L	-0.59	-0.69	-0.45
SU30	-1.78	-2.11	-1.35
MH10	-0.48	-0.69	-0.45
MH30	-0.98	-2.11	-1.35
ER10	-0.05	-0.17	-0.45
ER30	-0.45	-0.50	-1.35

Two graphic methods of presentation have been devised. These seem to give a more descriptive presentation and enable meaningful interpretation of the hydrologic evaluations. One method is graphical display of the time series of net reductions in water level relative to the base case. The second is the construction of histographs, which show the approximate frequency distribution of water levels. Changes in the shapes of these distributions from one scenario to the next are important to the overall assessment of hydrologic impact. The water level series used to prepare these figures are the mean annual water levels computed from the simulation model outputs. Experience has shown that these annual means effectively capture the year-to-year variation of the diversion impacts. It is therefore not necessary to examine the variation experienced in a particular month from year to year in order to gain insights into the effects of the diversion flows. In essence, a plot of the mean July water level for each year in the simulation, for example, would by and large be identical to the one given for the annual means, differing only by a constant offset in the mean.

Figure 8 shows several time series of annual water levels, each resulting from separate simulations. It is apparent that the general pattern of rising and falling water level is preserved despite the obvious water level reductions. It is not entirely evident, however, that impacts are constant as opposed to being correlated with the lake levels or increasing through time. The situation is more clearly depicted by plotting differences in lake level relative to the base case as shown in figure 9. This graph indicates that impacts resulting from the SU10L and MH10 scenarios are nearly constant. This is in contrast to the wild variations obtained for SU10 (fig. 6) and the nonstationary case caused by inappropriate initial conditions (fig. 7).

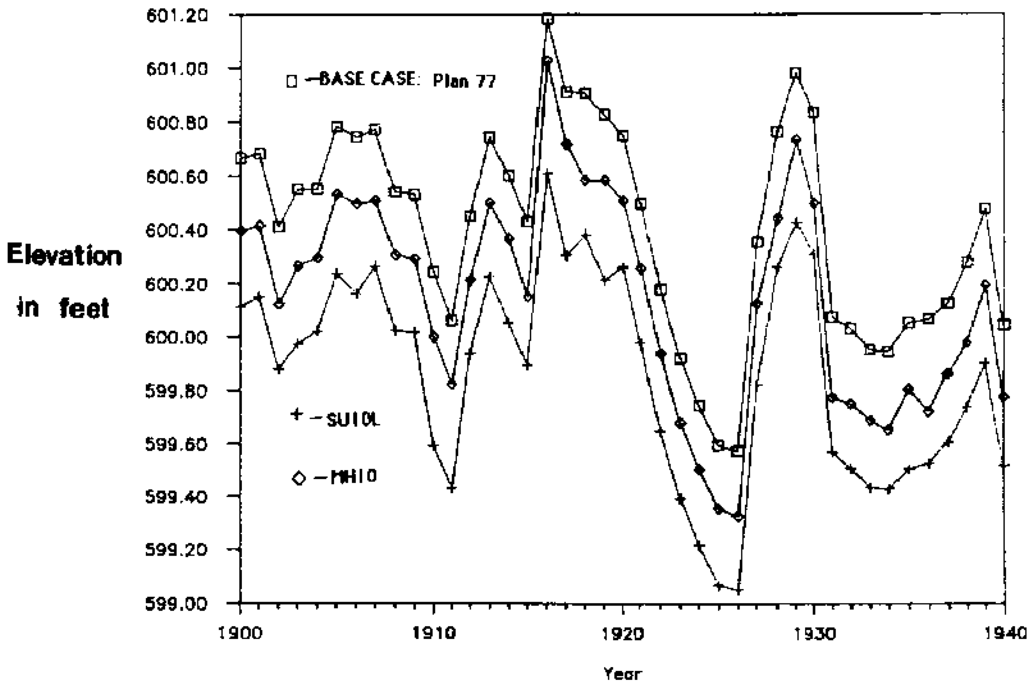


Figure 8. Lake Superior levels

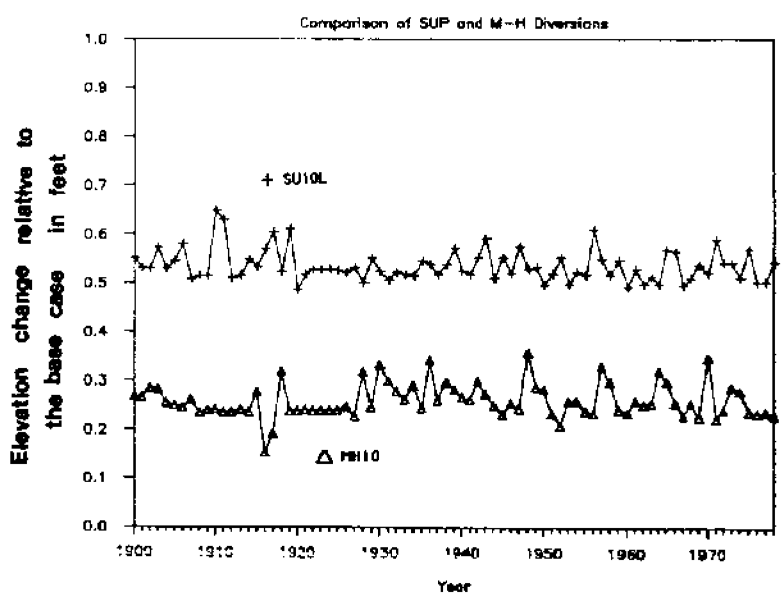
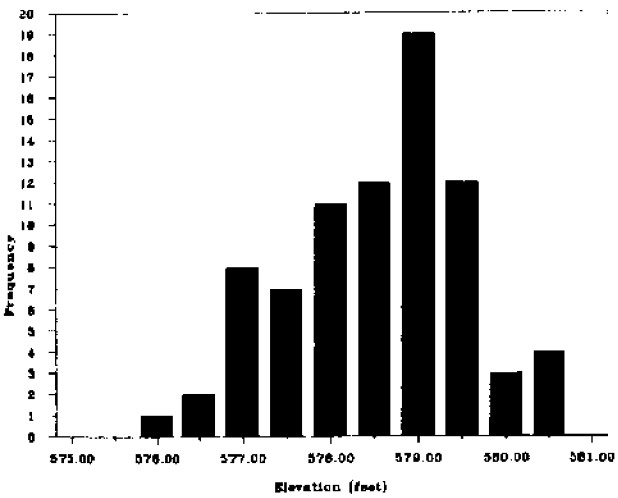


Figure 9. Reduction of Lake Superior levels

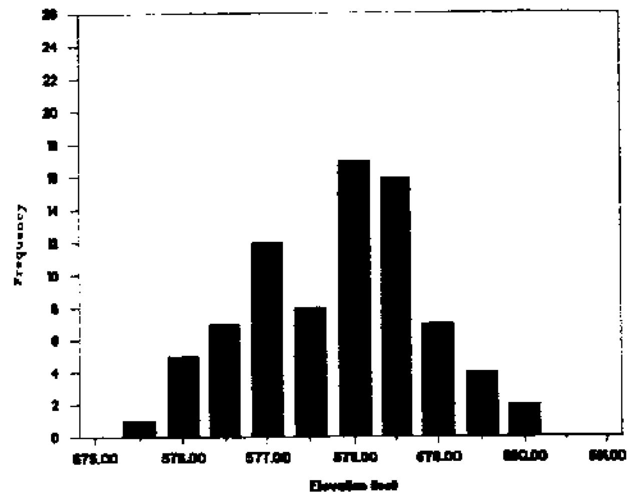
The difference between the SU10 and SU10L behavior lies in the minimum flow contingencies built into Plan 1977. Currently, the plan specifies a minimum flow of 55,000 cfs with the stipulation that whenever the plan flow is 65,000 cfs or less the flow is set at the 55,000-cfs minimum.

In this way, the plan speeds the recovery of low Superior levels (or high Michigan-Huron levels) thus decreasing the likelihood of future Superior outflows below 65,000 cfs. This form of the rule is used in SU10, whereas SU10L assumes the trigger and minimum are 55,000 and 45,000 cfs. The SU10L policy has significant impacts on St. Marys hydropower generation that may or may not outweigh the hydrologic consequences observed for SU10. In the SU30 scenario the trigger and minimum flowrates are reduced by 30,000 cfs.

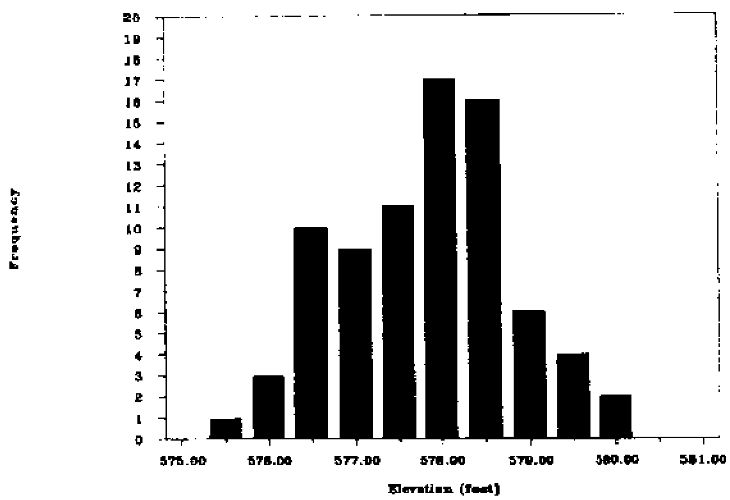
Frequency distributions for the water levels themselves also provide insight into the response of the lake level regimes. Figure 10 shows that water levels derived in the base-case simulation are distributed with definite negative skew. The skewness decreases to some extent in the distributions representing diversion scenarios. If skewness is in fact changed, then the probability of experiencing below-normal lake levels is greater. This gives rise to the prospect of a greater number of years with inadequate water levels than would be indicated by the mean change in lake levels alone.



a. for Base Case



b. with diversion from Lake Michigan-Huron



c. with diversion from Lake Superior

Figure 10. Distribution of Michigan-Huron levels

CHAPTER 5

CONCLUSIONS

Summary

The main objective of this study was to develop a methodological framework to estimate how Great Lakes water levels would change in response to a major interbasin diversion. In the past, simulation models have been used to estimate lake level variations brought about by regulation, ice jams, and minor diversions. The development of the modeling approach used has been described from the historical as well as the operational perspective.

There are three processes to be considered in the development of a Great Lakes system simulation strategy: (1) the hydraulics of the lakes and connecting channels, (2) the natural water supply process, and (3) the regulation policies imposed on the outlets of the two controlled lakes. The hydrologic components of the three investigations performed by past IJC study boards focused on these processes of the lake system. For the first of these studies, a mathematical formulation of a suitable simulation strategy was developed. A FORTRAN language model and an input data set consisting of net basin supply estimates were among the study's useful products. The two studies that followed used this model to investigate new questions concerning Great Lakes water levels. Within 10 years, the IJC had thus standardized its own approach to Great Lakes hydrologic evaluation.

In chapter 4 of this report, an explanation is given of the intrinsic difference between the simulation of scenarios of regulation policy options and the simulation of scenarios involving major diversion. The latter entails significant changes in the water throughput for each lake downstream of the diversion, requiring the modeler to take corrective action to obtain realistic simulation outputs. Specifically, the policies used to determine regulated lake outflows need to be changed to reflect the associated reduction in long-term mean outflows. In addition, the initial water levels used in the simulation runs should be adjusted to correspond to the predicted average water level for the starting date (i.e., January 1). The resulting water level frequency distributions will otherwise be biased by the outputs obtained during the 15- to 20-year adjustment period at the beginning of the series.

Simulation results are presented for several hypothetical diversion scenarios. Diversion flows examined ranged in quantity from 5,000 to 30,000 cfs. The sources of diversion water were assumed to be either Lake Superior, Lake Michigan, or Lake Erie because diversions farther downstream were known to have diminishing impact on the system as a whole. A base case was developed for comparison. The results demonstrate consistency in the performance of the model. In general, water levels dropped in comparison to the base case by some constant depth. These reductions varied slightly from year to year. Many of the variations observed, however, were no different from white noise. A diversion flow of 10,000 cfs from Lake Superior caused water levels on this big lake to fall an average of 0.59 feet. When the same flow of diversion water was removed from Lake Michigan-Huron, the average drop was 0.48 feet. The impact on Lake Michigan-Huron was approximately 0.70 feet for either case. Diversions from Lake Erie have a greatly diminished impact on Lake Superior, the average drop being less than one inch. The response of Lake Erie's water level was a drop of 0.48 feet regardless of the diversion source.

The scenarios invoking the 5,000 and 30,000-cfs diversions yielded results that indicate that impacts generally increase linearly with increased diversion rate. This is not the case with the response of Lake Superior water levels.

Conclusions and Recommendations

The modeling strategy presented provides an adequate means to detect changes in Great Lakes water level regimes caused by interbasin diversion. In recent years, the political climate regarding the feasibility of potential construction of a major diversion facility utilizing Great Lakes water has changed, making such considerations less likely. The efficacy of using diversions to solve problems of water resource availability is not addressed here. An advocacy position either for or against diversion can come only from comparison of all benefits and costs that might be anticipated once such a diversion exists. The principal result of the study presented here is better understanding of the responses of the Great Lakes system to reductions in water supply. Moreover, it is hoped that this work will enhance awareness of the modeling capabilities available within the Great Lakes research community. Scientists and interested citizens who want to assess economic and environmental impacts caused by water level fluctuations now have tools for water level estimation under any policy scenario.

The modeling methodology is relatively simple in conformance with data availability. Some accuracy may have been sacrificed. Models of greater complexity with commensurately more demanding data requirements have appeared in the last 10 years. The limiting factor in the simplified approach is believed to be the net basin supply series, which makes up the driving input for the model. Hence, the newer simulation strategies have featured driving data based on hydrologic variables viewed as more immediate and natural -- albeit difficult to acquire -- such as precipitation, cloud cover, and temperature. The rationale of the net basin supply approach is given in chapter 2. Although such data are available, experts admit to the presence of large errors in individual net basin supply values for certain months and years. In isolated cases the errors may exceed 50 percent (Quinn 1982, p. 3). In absolute terms this may amount to over- or underestimation by as much as 30,000 cfs. Fortunately, the accuracy of the model is aided by the fact that these errors do not tend to accumulate; however, prudence is advised when the outputs are subjected to further analysis. The best hedge against possible errors of this type is the use of annual means rather than monthly values.

The diminishing political interest surrounding the diversion question should not deflect attention from study of the Great Lakes water budget because the lakes' water supplies are affected by ever-increasing levels of consumptive use. Consumptive use is that portion of water supply withdrawal not returned to the source of supply because of inevitable losses through evaporation. As withdrawal quantities increase, so does overall consumptive use. The rate of consumptive use in the Great Lakes basin is not known precisely, but it is thought to exceed 5,000 cfs at present (DCU 1981, p. 6-1). The quantity might reach 10,000 cfs by the end of the century. Consumptive use exerts precisely the same effects on the system as does diversion. The hydrologic response model presented here can similarly be used to determine consumptive use impacts. The model also has utility in estimating expected changes in water levels caused by changes in the climate of the region, provided that changes in climatic parameters can be translated into new values for net basin supply quantities.

APPENDIX 1

Summary of Special IJC Study Boards Established to Investigate Water Level Variations and Effects

1. International Great Lakes Levels Board (IGLLB)

   Start: October 1964 End: December 1973

   Mission: Determine whether measures of flow regulation can be taken to reduce extreme high and low Great Lakes water levels. Develop potential regulation schemes and evaluate probable effects on all aspects of the Great Lakes Basin system.

   Publication: Regulation of Great Lakes Water Levels, A Summary Report 1974. The 40-page summary report is accompanied by seven technical appendices:

   Appendix A - Hydrology and Hydraulics
   Appendix B - Lake Regulation (three volumes)
   Appendix C - Shore Property
   Appendix D - Fish, Wildlife, and Recreation
   Appendix E - Commercial Navigation
   Appendix F - Power
   Appendix G - Regulatory Works

2. International Lake Erie Regulation Study Board (ILER)

   Start: May 1977 End: July 1981

   Mission: Develop management plans for partial regulation of Lake Erie and determine the effects of proposed plans on the Great Lakes system.

   Publication: Lake Erie Water Level Study, September 1981. Main report and eight technical appendices:

   Appendix A - Lake Regulation (two volumes)
   Appendix B - Regulatory Works
   Appendix C - Coastal Zone
   Appendix D - Commercial Navigation
   Appendix E - Power (two volumes)
   Appendix F - Environmental Effects
   Appendix G - Recreational Beaches and Boating
   Appendix H - Public Information Program

3. International Great Lakes Diversions and Consumptive Uses Study Board (DCU)

Start: May 1977 End: August 1981

Mission: Investigate the effects of existing diversions and consumptive uses. Estimate probable trends in consumptive uses during 50-year planning horizon, and evaluate combined effects of diversions and consumptive uses on the Great Lakes system.

Publication: Great Lakes Diversions and Consumptive Uses, Report to the International Joint Commission, September 1981. Main report plus seven annexes (minor appendices) are presented in three volumes. In addition, there are three technical appendices:

Appendix A – Coordinated Basic Data
Appendix B – Computer Models - Great Lakes
Appendix C – Diversion Management Scenarios

APPENDIX 2

Summary of Net Basin Supply and Ice Retardation Database

TABLE 10. Mean monthly net basin supplies for Lakes Superior, Michigan-Huron, and St. Clair expressed in 1000 cfs

	Monthly Means During 1900-78			Standard Deviations		
Month	Lake Superior	Lake Michigan-Huron	Lake St. Clair	Lake Superior	Lake Michigan-Huron	Lake St. Clair
Jan	-12.96	53.36	5.47	24.71	52.93	6.33
Feb	9.37	88.02	6.48	26.63	46.36	6.20
Mar	43.66	181.36	8.60	42.85	77.65	6.83
Apr	147.67	283.68	7.53	50.34	82.11	7.08
May	188.94	254.29	5.34	58.87	81.97	5.48
Jun	158.85	207.03	3.39	50.81	63.53	2.83
Jul	131.17	130.34	2.63	38.94	52.34	2.91
Aug	100.39	51.75	1.22	43.11	60.03	2.23
Sept	74.66	28.09	0.95	56.10	69.05	2.28
Oct	34.84	-3.56	1.09	44.58	69.71	2.42
Nov	15.26	30.51	1.51	40.61	61.99	2.40
Dec	-24.18	24.59	4.38	28.52	63.00	5.46

TABLE 11. Connecting channel ice retardation effects derived from historical levels and flows expressed in 1000 cfs

	Monthly Means During 1900-78				Standard Deviations			
Month	St. Clair River	Detroit River	Ontario Outlet	St.Louis Outlet	St. Clair River	Detroit River	Ontario Outlet	St Louis Outlet
Jan	30.25	12.10	6.77	32.11	19.84	12.72	6.51	13.01
Feb	37.68	10.27	9.87	25.19	18.53	12.71	5.69	9.15
Mar	16.29	4.32	5.49	7.61	14.29	7.76	4.10	5.22
Apr	3.15	1.16	---	4.47	11.13	2.83	---	4.46
May	0.19	---	---	---	1.68	---	---	---
Jun	---	---	---	---	---	---	---	---
Jul	---	---	---	---	---	---	---	---
Aug	---	---	---	---	---	---	---	---
Sep	---	---	---	---	---	---	---	---
Oct	---	---	---	---	---	---	---	---
Nov	---	---	---	---	---	---	---	---
Dec	3.75	5.33	0.42	10.35	5.44	8.18	1.28	8.89

TABLE 12. Quarter-monthly net basin supplies for Lakes Erie and Ontario and the L. Ontario to L. St. Louis reach of the St. Lawrence River (in tcfs units)

Month and Quarter	1900-78 Means			Standard Deviations		
	Lake Erie	Lake Ontario	Lake St.Louis	Lake Erie	Lake Ontario	Lake St.Louis
Jan 1	32.86	34.28	2.71	64.66	33.90	1.51
Jan 2	21.74	30.10	3.28	45.44	31.06	1.58
Jan 3	28.98	30.91	3.25	59.14	32.16	1.60
Jan 4	18.76	34.42	3.15	49.45	33.89	1.67
Feb 1	19.56	32.96	3.47	42.90	25.53	1.53
Feb 2	28.82	32.73	2.93	42.33	26.74	1.27
Feb 3	35.99	35.65	2.44	51.92	31.12	1.37
Feb 4	48.78	43.87	2.00	53.41	33.62	1.47
Mar 1	52.80	58.28	3.01	57.89	38.97	1.33
Mar 2	56.96	62.47	3.05	41.24	37.81	1.93
Mar 3	78.48	83.12	3.97	53.45	45.72	2.80
Mar 4	99.98	94.90	5.44	72.87	44.41	2.92
Apr 1	88.27	115.60	7.29	58.62	45.85	3.32
Apr 2	60.92	88.69	7.86	46.08	33.98	2.72
Apr 3	64.46	93.50	8.71	44.50	37.31	3.02
Apr 4	51.76	73.59	8.77	43.40	27.12	2.68
May 1	46.26	69.10	9.04	34.38	31.29	2.70
May 2	50.32	58.61	8.70	44.75	30.44	3.37
May 3	49.03	64.46	8.11	40.34	36.13	3.64
May 4	37.26	48.73	7.21	30.48	28.44	3.65
Jun 1	38.07	48.02	6.30	32.65	32.02	3.16
Jun 2	27.55	41.06	5.55	27.40	20.21	2.64
Jun 3	25.27	38.27	4.94	35.86	23.59	2.24
Jun 4	22.65	38.04	4.39	31.98	23.08	1.87

TABLE 13. Quarter-monthly net basin supplies for Lakes Erie and Ontario and the L. Ontario to L. St. Louis reach of the St. Lawrence River (in tcfs units)

Month and Quarter		1900-78 Means			Standard Deviations	
	Lake Erie	Lake Ontario	Lake St.Louis	Lake Erie	Lake Ontario	Lake St.Louis
Jul 1	9.15	29.89	3.84	32.38	23.63	1.51
Jul 2	6.86	28.93	3.36	26.42	18.35	1.27
Jul 3	1.25	20.54	2.99	27.33	20.34	1.14
Jul 4	-3.67	18.78	2.69	24.10	21.86	1.17
Aug 1	-9.25	11.19	2.42	29.27	24.51	0.99
Aug 2	-6.38	14.81	2.21	26.64	20.55	0.82
Aug 3	-18.04	1.83	2.12	25.96	21.46	0.72
Aug 4	-19.16	4.07	2.01	38.54	21.15	0.64
Sep 1	-16.46	1.48	1.94	23.70	20.37	0.69
Sep 2	-21.54	3.77	1.87	32.04	21.84	0.65
Sep 3	-25.12	2.53	1.98	37.43	23.06	0.70
Sep 4	-16.39	5.40	2.08	38.13	24.97	0.80
Oct 1	-24.92	6.82	2.30	41.28	26.05	1.07
Oct 2	-20.15	4.18	2.38	34.77	20.30	1.15
Oct 3	-20.97	5.91	2.49	31.80	24.71	1.31
Oct 4	-27.02	7.93	2.81	34.19	27.07	1.47
Nov 1	-19.97	12.28	3.04	34.75	26.08	1.61
Nov 2	-11.21	14.88	3.15	35.21	24.12	1.64
Nov 3	0.11	20.27	3.42	40.20	29.28	1.76
Nov 4	-1.99	21.32	3.41	38.02	28.71	1.71
Dec 1	16.97	24.61	3.14	42.65	27.07	1.38
Dec 2	12.89	24.57	3.26	47.28	30.77	1.44
Dec 3	14.40	23.76	3.14	39.13	28.03	1.32
Dec 4	15.66	24.34	3.05	53.91	33.49	1.32

APPENDIX 3

Middle Lakes Routing Model
Inputs and Parameters

A. Given data for each time step

1. BOP lake elevations

    $E1_{mh}$ - L. Michigan-Huron water level

    $E1_{sc}$ - L. St. Clair level

    $E1_{er}$ - L. Erie level

2. Basin supplies

    T_{mh} - L. Michigan-Huron total basin supply

    N_{sc} - L. St. Clair net basin supply

    N_{er} - L. Erie net basin supply

3. Ice and weed flow retardation

    R_{mh} - St. Clair River ice retardation

    R_{sc} - Detroit River ice retardation

    R_{er} - Niagara River ice and weed retardation

B. Desired outputs

1. $E2_{mh}$, $E2_{sc}$, $E2_{er}$ - EOP water surface elevations

2. O_{mh}, O_{sc}, O_{er} - Mean outflows for period

3. H_{mh}, H_{sc}, H_{er} - Mean water surface elevations for period

C. Known constants

1. V_{mh}, V_{sc}, V_{er} - Volume of water representing one foot of water over the lake area

2. N - Number of time steps per month

APPENDIX 3

Middle Lakes Routing Model
Mathematical Formulation

A. Hydraulic heads and sections

1. $A = H_{mh} - H_{sc}$
2. $B = H_{sc} - H_{er}$
3. $C = 0.5(H_{mh} + H_{sc}) - 543.40$
4. $D = H_{sc} - 543.81$
5. $F = H_{er} - 556.25$

B. Constants

1. $K_1 = 0.0841168$
2. $K_2 = 0.1280849$
3. $K_3 = 3.665$

C. Equations used to obtain unknowns

1. Set of six simultaneous equations of which the model is comprised

$$O_{mh} = K_1 A^{1/2} C^2 - R_{mh}$$

$$O_{sc} = K_2 B^{1/2} D^2 - R_{sc}$$

$$O_{er} = K_3 F^{3/2} - R_{er}$$

$$E2_{mh} = E1_{mh} + \frac{(T_{mh} - O_{mh})}{(V_{mh}{*}\ N)}$$

$$E2_{sc} = E1_{sc} + \frac{(O_{mh} + N_{sc} - O_{sc})}{(V_{sc}{*}\ N)}$$

$$E2_{er} = E1_{er} + \frac{(O_{sc} + N_{er} - O_{er})}{(V_{er}{*}\ N)}$$

2. Approximations of mean levels for period

$$H_{mh} = \frac{1}{2} (E1_{mh} + E2_{mh})$$

$$H_{sc} = \frac{1}{2} (E1_{sc} + E2_{sc})$$

$$H_{er} = \frac{1}{2} (E1_{er} + E2_{er})$$

APPENDIX 4

Procedure for Determining Lake Superior Outflow According to Regulation Plan 1977

Step 1. Compute basic rule flow with the balance equation:

$$Q_b = Q_j + A^* [(S_t - S_j) - (H_t - H_j)^*R_j]$$

$$\text{with } R_j^2 = \frac{V[S_j]}{V[H_j]}$$

Where: t is the index of the current month
j is an index ranging from 1 to 12 used to designate parameters with different values each month

Q_b - Basic rule flow

Q_j - Average Superior outflow in month j

S_j, H_j - Target levels for Superior and Michigan-Huron in month j

S_t, H_t - Actual BOM water levels

$V[S_j]$, $V[H_j]$ - Estimate of historical variance of monthly water levels in month j

R_j, A - Weighting factors

Step 2. Flow limitations

a) Absolute maximum
   1. In winter, Q_{max} = 85 tcfs

   2. In nonwinter, Q_{max} is compensating works capacity plus 65 tcfs

b) Absolute minimum Q_{min} = 55 tcfs

c) Maximum deviation from previous month's flow is restricted to +/- 30 tcfs

Step 3. Low flow contingency

If balance equation flow is 65 tcfs or less, the rule flow, Q_r, is set to 55 tcfs to speed recovery of the L. Superior level

Step 4. Determine gate setting NG (number of gates raised)

a) If Q_r = 55 tcfs then NG = 1/2, which is the minimum permitted gate setting

b) Otherwise, compensating works flow is Q_r minus the flow diverted for hydropower generation, currently 65 tcfs. Given L. Superior level and desired flow, gate setting may be obtained from rating curves given in fig. 5

Step 5. Forecasting based on median supplies

a) In nonwinter, forecasts will continue from current month through November (no forecast if current month is November)

b) In December, carry out forecasts through the month of April

c) In winter, gate movements are rarely made

d) Median basin supplies are used for all lakes unless the level of L. Superior exceeds 601.30, in which case the 5% probability of exceedence NBS values are assumed for Lakes Superior and Michigan-Huron. The median (50% exceedance probability) supplies are always used for Lakes St. Clair and Erie

e) Procedure

(1) Assume net basin supply values as directed in d)
(2) Iteratively estimate mean Lake Superior outflow using hydrologic budget and compensating works rating curve
(3) Use middle lakes routing model to get EOM level of L. Michigan-Huron
(4) Determine the gate setting for the next month based on the lake levels just obtained
(5) Continue procedure until last month of the forecast period

Step 6. The gate setting to be used is the arithmetic average of the several gate settings determined during the forecast procedure. The sum of all gate settings is divided by the number of months in the forecast. The nearest integer becomes the Plan 1977 gate setting for the upcoming month.

APPENDIX 5

Procedure for Determining Lake Ontario Outflow According to Regulation Plan 1958D

Definitions: Plan outflows for the following period are determined on the last day of the current period. The previous period is the quarter-month that ended seven or eight days before the current date.

Step 1. Update the supply indicator

a) The so-called cumulative supply number is updated by subtracting the previous period outflow and adding the current period mean inflow

b) The weighted supply is equal to 1/16.5 times the supply number

c) The supply indicator, I_t, equals the weighted supply minus the normal weighted supply (NWS) for the current period. NWS values for each period are given in column three of table 14

d) The supply indicator is subject to an adjustment based on the net change of I_t during the past three months

(1) Define:

$$\Delta_t = I_t - I_{t-12}$$

(2) The adjustment is equal to 2/9 times the sum:

$$\Delta_{t-1} + \Delta_{t-2} + \Delta_{t-3}$$

(3) The adjustment must, however, be greater than -11,000 and less than +7,000 cfs

e) The adjustment is then added to the supply indicator to obtain the adjusted supply indicator

Step 2. Determine rule outflow, Q_r

a) There are two rule curves, one for February through July, the other for August through January. These curves are presented in figures 11 and 12

b) Enter appropriate rule curve with current water level and adjusted supply indicator value. Read off the indicated Lake Ontario outflow

				MINIMUM FLOW LIMITATIONS		MAXIMUM FLOW LIMITATIONS			
Month	Quarter	Normal Weighted Supply	Seasonal Adjustment to Basic Rule Outflow	Add to Supply Indicator at End of Preceding Period (P)*	Minimum (M)	For Channel Design (L)	For Ice Formation Lachine (I)	Add to Supply Indicator at End of Preceding Period (P)	
1	2	3	4	5	6	7	8	9	
Jan.	1	234	0	--	210	See	--	--	
	2	234	- 6	--	210	figure	--	--	
	3	233	- 6	--	210	13	--	--	
	4	233	- 6	--	210		--	--	
Feb.	1	233	- 6	--	207		--	248	
	2	233	- 6	--	207		--	248	
	3	233	- 6	--	207		--	248	
	4	233	- 6	--	207		--	248	
March	1	233	- 6	--	204		--	248	
	2	235	- 6	--	204		--	248	
	3	237	- 6	--	204		--	248	
		242	- 6	--	204		--	248	
April	1	246	- 8	--	188		--	248	
	2	249	-10	--	188		--	253	
	3	252	-12	--	188		--	257	
	4	254	-14	--	188		--	259	When
May	1	257	-16	--	188		--	261	outflow
	2	258	-18	--	188		--	263	from
	3	260	-20	227*	188		--	265	Lake
	4	261	-20	232*	188		--	266	St.
June	1	262	-20	237*	190		--	267	Louis
	2	262	-20	242*	190		--	267	for
	3	263	-20	245*	190		--	268	previous
	4	263	-20	247*	190		--	268	quarter
July	1	262	-18	249*	193		--	268	exceeds
	2	262	-16	251*	193		--	267	345,000
	3	261	-14	252*	193		--	266	cfs
	4	259	-12	253*	193		--	265	

TABLE 14 (CONT.)

				MINIMUM FLOW LIMITATIONS		MAXIMUM FLOW LIMITATIONS		
Month	Quarter	Normal Weighted Supply	Seasonal Adjustment to Basic Rule Outflow	Add to Supply Indicator at End of Preceding Period (P)*	Minimum (M)	For Channel Design (L)	For Ice Formation Lachine (I)	Add to Supply Indicator at End of Preceding Period (P)
1	2	3	4	5	6	7	8	9
August	1	258	-10	254*	193		--	--
	2	256	- 8	255*	193		--	--
	3	254	- 6	256*	193		--	--
	4	252	- 4	256*	193		--	--
Sept.	1	250	- 2	256*	193		--	--
	2	248	0	256*	193		--	--
	3	246	+ 2	255*	193		--	--
	4	244	+ 2	252*	193		--	--
Oct.	1	243	+ 2	249*	193		--	--
	2	241	+ 2	247*	193		--	--
	3	239	+ 2	245*	193		--	--
	4	238	+ 4	243*	193		--	--
Nov.	1	237	+ 4	241*	198		--	--
	2	236	+ 6	240*	198		--	--
	3	235	+ 6	239*	198		--	--
	4	235	+ 8	238*	198		--	--
Dec.	1	235	+ 8	238*	210		280 from	--
	2	235	+ 8	238*	210		Lake	--
	3	234	+ 6	--	210		St. Louis	--
	4	234	+ 6	--	210			--

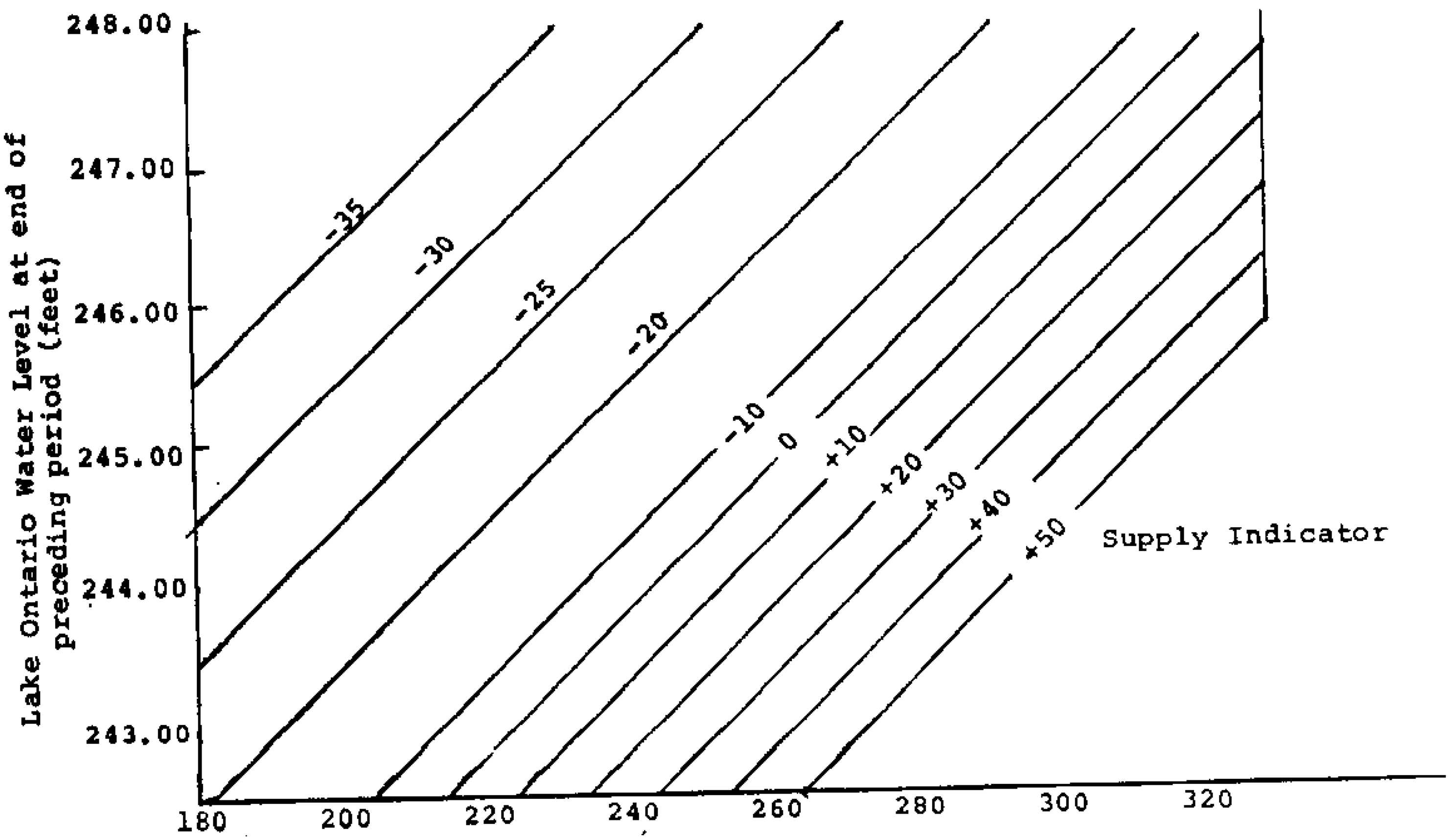


Figure 11. Regulation of Lake Ontario Plan 1958D (basic rule curve, February through July) (Source: International St. Lawrence River Board of Control 1963)

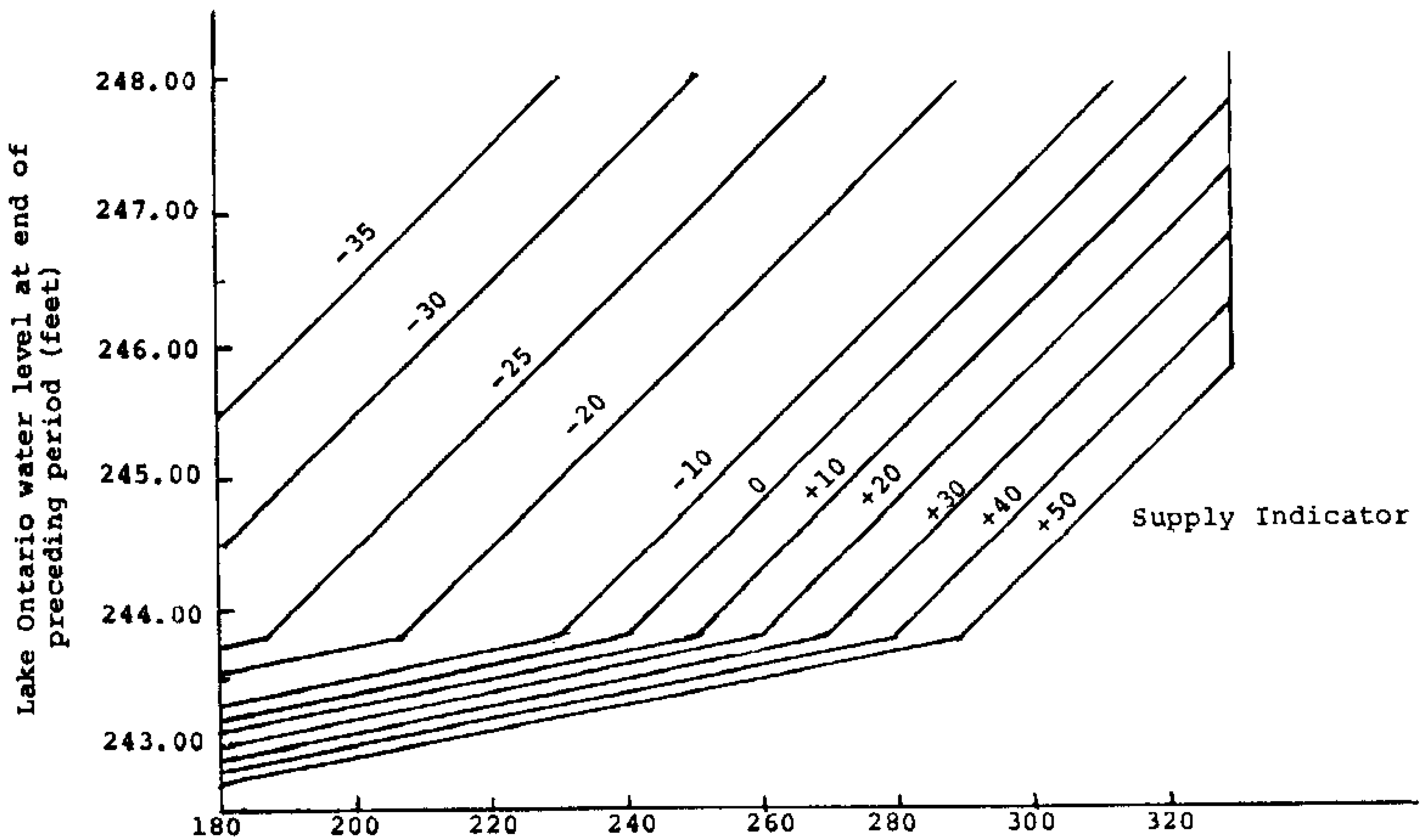


Figure 12. Regulation of Lake Ontario Plan 1958D (basic rule curve, August through January) (Source: International St. Lawrence River Board of Control 1963)

3. Outflow limitations

a) L-Limitation: Maximum outflow base on seaway channel design. The L-limitation supercedes all other limits. This limitation varies with both time of year and the Lake Ontario water level; a graphic illustration of the values it may assume is given in figure 13.

b) P-Limitations: There are two P-limitations: one is a maximum; the other, a minimum. The latter is referred to as the P* (pronounced P-star) limitation. Neither limit applies year-round

(1) P-limitation (maximum) February 1 through April 2. Value shown in column nine of table 14 is added to current value of I_t; Q_r may not exceed this quantity

(2) P-limitation (maximum) April 3 through July 4. Not used except when Lake St. Louis outflow exceeds 345,000 cfs, in which case procedure is as described in b) (1)

(3) P*-limitation (minimum) May 3 through December 2. Value in column five of table 14 is added to current value of I_t. Result is compared to the quantity (225-D/6), where D equals the difference between the outflows from Lake Ontario and Lake St. Louis. The letter of the two quantities becomes the minimum outflow according to the P*-limitation

c) M-Limitation: Absolute minimum flows given monthly as indicated in column six of table 14

d) J-Limitation: Maximum deviation from previous period outflow may not exceed $\pm$20,000 cfs

e) I-Limitation: During last two periods of the year, the outflow from Lake St. Louis may not exceed 280,000 cfs. This regulation occasionally has implications for Lake Ontario inasmuch as the outflows must be reduced to compensate for unusually high discharges from the Ottawa River into Lake St. Louis. The final step in 1958D procedure is always a check of resulting St. Louis outflow; appropriate adjustment is made if it exceeds 280,000 cfs

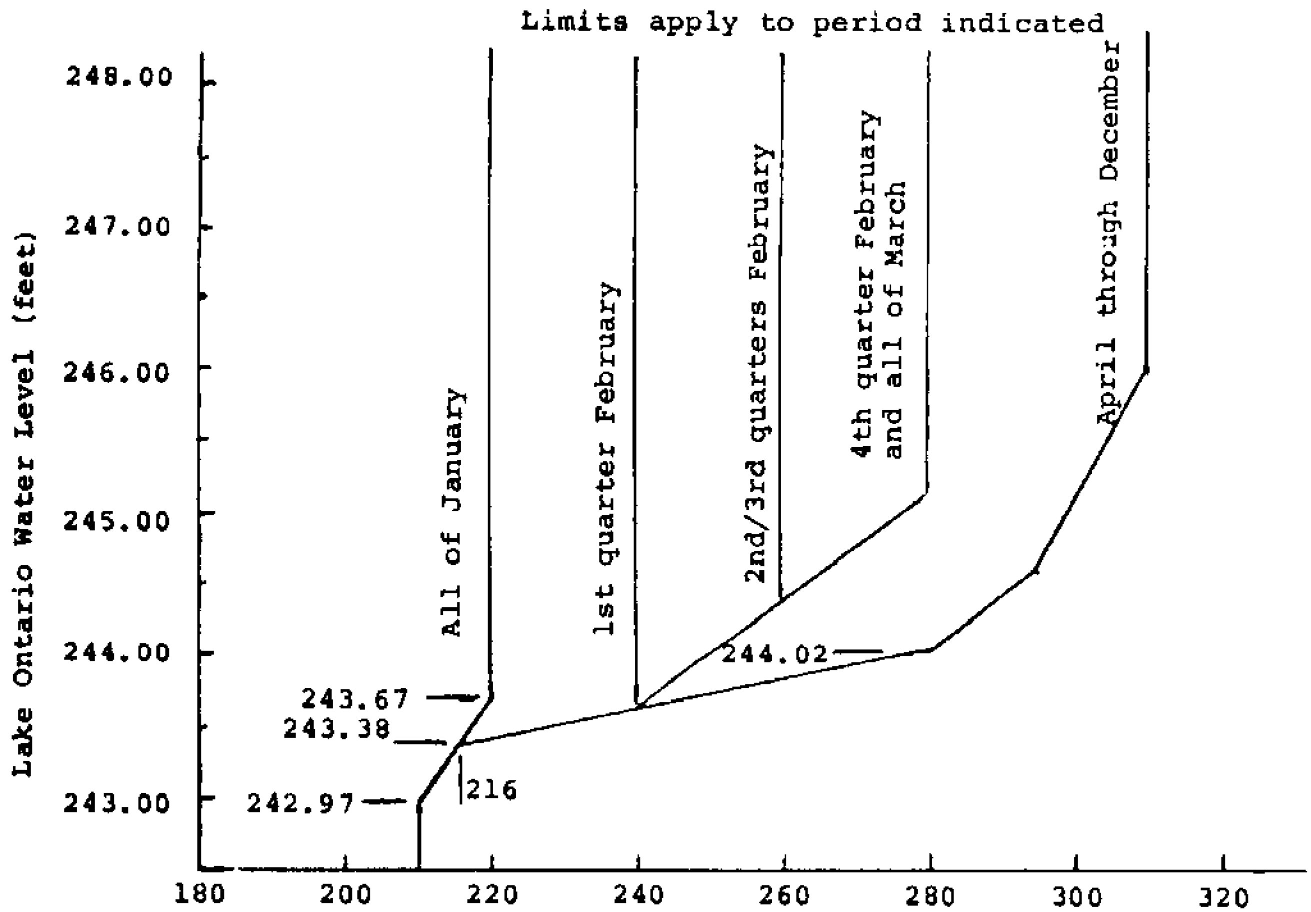


Figure 13. Maximum outflows according to the L-limitation for Plan 1958D
(Source: International St. Lawrence River Board of Control 1963)

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